BY ORDER OF THE
SECRETARY OF THE AIR FORCE

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Civil Engineering

ENERGY EFFICIENT MOTORS AND ADJUSTABLE SPEED DRIVES

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This pamphlet implements AFMAN(I) 32-1181, *Design Standards for Facilities Interior Electrical Systems*. It provides recommendations for successful application, selection, and installation of energy efficient motors and adjustable speed drives on Air Force installations. Refer to AFMAN(I) 32-1181, AFMAN(I) 32-1281, *Facilities Engineering, Electrical Interior Facilities,* and AFMAN(I) 32-1280, *Facilities Engineering, Electrical Exterior Facilities*, for general criteria and requirements. Users should send comments and suggested improvements on AF Form 847, *Recommendation for Change of Publication*, through major commands (MAJCOM) and HQ AFCESA/CESM, 139 Barnes Dr, Tyndall AFB FL 32403-5319 to HQ USAF/ILEO, 1260 Air Force Pentagon, Washington DC 20330-1260.

SUMMARY OF REVISIONS

This is the initial publication of AFPAM 32-1192.

FIGURES

TABLES

Chapter 1

PURPOSE AND APPLICABILITY

1.1. Purpose. This AFPAM has been issued to provide users with application, selection, installation, energy analysis, and repair guidance for energy efficient motors and adjustable speed drives (ASD). The purpose of the recommendations contained in this AFPAM is to assure a reliable motor system when upgrading to energy efficient motors or ASDs. Detailed guidance is provided regarding energy efficiency analysis so that potential savings of a particular design option can be estimated. ASD design options are described in detail to ensure that ASD installations do not degrade electrical systems.

1.2. Scope:

1.2.1. This AFPAM provides specific guidance and recommendations regarding energy efficient motors and ASDs. The guidance addresses energy efficiency analysis and equipment design options.

1.2.2. This AFPAM relies on existing industry information and analysis tools. MotorMaster®, a software program for motor analysis, is discussed in detail because of its wide industry acceptance and its ease of use. ASDMaster® is similarly included for the analysis of ASDs. Both software programs are readily available from the DOE Motor Challenge program and information is provided in this AFPAM regarding how to obtain individual copies of the software.

1.2.3. Electrical protection associated with energy efficient motors and ASDs is described in detail because of the unique protection needs associated with this equipment.

1.3. References. Attachment 1 contains a list of references used in this pamphlet. References applicable to a specific topic are also listed and described in the appropriate sections of the AFPAM.

1.4. Applicability:

1.4.1. This AFPAM complies with AFI 32-1080, *Electric Power Systems*, and supplements AFMAN(I) 32-1181, *Design Standards for Facilities Interior Electrical Systems*.

1.4.2. Compliance with the AFPAM is recommended for energy efficient motors and ASDs in interior and exterior electrical systems that are the responsibility of the Base Civil Engineer at all facilities and bases. The guidance regarding ASDs also applies to standard efficiency motors.

Chapter 2

ENERGY EFFICIENCY CRITERIA AND ENERGY EFFICIENCY ANALYSIS

2.1. Federal Requirements for Energy Efficiency:

2.1.1. Energy Policy Act of 1992 (EPACT). This Act established conservation and energy efficiency requirements for government and consumers. For Federal agencies, EPACT requires a 20 percent reduction in per-square-foot energy consumption by 2000, compared to a 1985 baseline. EPACT authorizes DOE to issue rules and guidance on Energy Savings Performance Contracts (ESPC) for Federal agencies. It requires Federal agencies to train and utilize energy managers, and it directs the Office of Management and Budget to issue guidelines for accurate assessment of energy consumption by Federal buildings.

2.1.2. Executive Order (EO) 12902, *Energy Efficiency and Water Conservation at Federal Facilities*, dated March 8, 1994. Note: EO 12902 has been revoked by EO 13123 as discussed in paragraph 2.1.3, but is still discussed here for historical completeness. For Federal agencies, this EO requires a 30 percent reduction in per gross square foot energy consumption by 2005 compared to 1985 to the extent that these measures are cost effective. It also requires a 20 percent energy efficiency increase in industrial facilities by 2005 compared to 1990 to the extent that these measures are cost effective. Finally, the EO requires the procurement of products in the top 25 percent of their class in energy efficiency where cost-effective and where they meet the agency's performance requirements. The following is an excerpt of Section 507, *Procurement of Energy Efficient Products by Federal Agencies*:

> "(a) "Best Practice" Technologies. Agencies shall purchase energy efficient products in accordance with the guidelines issued by OMB, in consultation with the Defense Logistics Agency (DLA), DOE, and GSA, under Section 161 of the Energy Policy Act of 1992. The guidelines shall include listings of energy efficient products and practices used in the Federal Government. At a minimum, OMB shall update the listing annually. DLA, DOE, and GSA shall update the portions of the listings for which they have responsibility as new products become available and conditions change.
>
> (1) Each Agency shall purchase products listed as energy-efficient in the guidelines whenever practicable, and whenever they meet the Agency's specific performance requirements and are cost-effective. Each Agency shall institute mechanisms to set targets and measure progress.
>
> (2) To further encourage a market for highly-energy-efficient products, each agency shall increase, to the extent practicable and cost-effective, purchase of products that are in the upper 25 percent of energy efficiency for all similar products, or products that are at least 10 percent more efficient than the minimum level that meets Federal standards. This requirement shall apply wherever such information is available, either through Federal or industry approved testing and rating procedures.
>
> (3) GSA and DLA, in consultation with DOE, other agencies, States, and industry and other nongovernment organizations, shall provide all agencies with information on

> specific products that meet the energy efficient criteria of this section. Product information should be made available in both printed and electronic formats."

2.1.3. EO 13123, *Greening the Government Through Efficient Energy Management*, dated June 3, 1999. This 1999 EO is the latest document governing energy efficiency and continues to confirm that energy efficient products must be considered and applied wherever they are life-cycle cost-effective. EO 13123 also revokes EO 12902. EO 13123 requires, through life-cycle cost-effective measures, that each agency reduce energy consumption per gross square foot of its facilities by 30 percent by 2005 and 35 percent by 2010 relative to 1985. The following is an excerpt of Section 403(b), *ENERGY STAR® and Other Energy Efficient Products*:

> "(1) Agencies shall select, where life-cycle cost effective, ENERGY STAR® and other energy efficient products when acquiring energy-using products. For product groups where ENERGY STAR® labels are not yet available, agencies shall select products that are in the upper 25 percent of energy efficiency as designated by FEMP. The Environmental Protection Agency (EPA) and DOE shall expedite the process of designating products as ENERGY STAR® and will merge their current efficiency rating procedures.
>
> (2) GSA and the Defense Logistics Agency (DLA), with assistance from EPA and DOE, shall create clear catalogue listings that designate these products in both print and electronic formats. In addition, GSA and DLA shall undertake pilot projects from selected energy-using products to show a "second price tag", which means an accounting of the operating and purchase costs of the item, in both printed and electronic catalogues and assess the impact of providing this information on Federal purchasing decisions.
>
> (3) Agencies shall incorporate energy efficient criteria consistent with ENERGY STAR® and other FEMP-designated energy efficiency levels into all guide specifications and project specifications developed for new construction and renovation, as well as into product specification language developed for Basic Ordering Agreements, Blanket Purchasing Agreements, Government Wide Acquisition Contracts, and all other purchasing procedures."

2.1.4. 10 CFR Part 435, *Energy Conservation Voluntary Performance Standards for New Buildings: Mandatory for Federal Buildings*. This regulation establishes performance standards to be used in the design of new Federal commercial and multifamily high rise buildings. Some of the guidelines are relevant to retrofits. Article 435.106 specifies minimum acceptable full load motor efficiencies for single speed polyphase motors that are expected to operate more than 500 hours per year.

2.1.5. 10 CFR Part 436, *Federal Energy Management and Planning Programs*. This regulation establishes procedures for determining the life-cycle cost effectiveness of energy conservation measures, and for prioritizing energy conservation measures in retrofits of existing Federal buildings.

2.1.6. 48 CFR Part 23.704, *Federal Contracting Preference Programs for Environmentally Preferable and Energy Efficient Products and Services*. The Federal Acquisition Regulations (FAR) require that agencies implement cost-effective contracting preference programs favoring the acquisition of environmentally preferable and energy efficient products and services. With regard to obtaining energy efficient products, the criteria include a requirement that procured products are in the upper 25 percent of energy efficiency for all similar products, or products must be at least 10 percent more efficient than the minimum level that meets Federal standards (Executive Order 12902, Section 507).

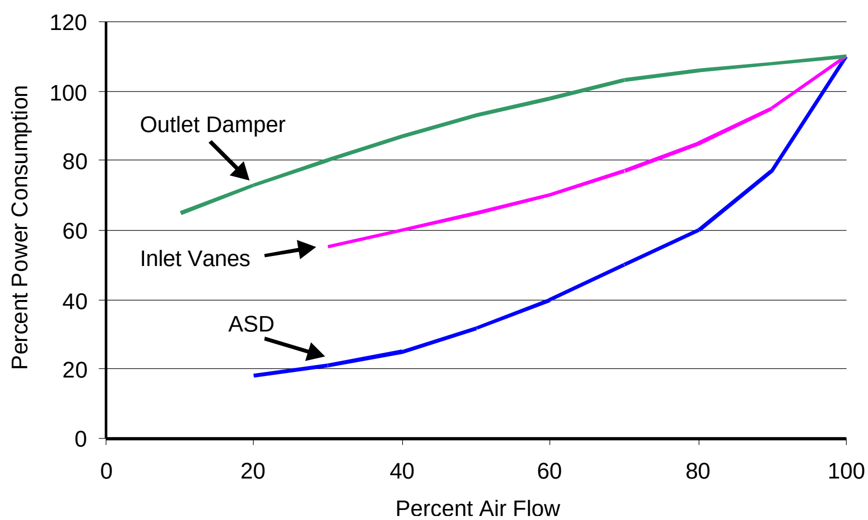
2.2. Guidance for Energy Efficiency Analysis:

2.2.1. Electric motor systems that operate continuously or for many hours a year consume electricity that costs many times the price of the motor. This makes less efficient motors excellent targets for replacement. If the driven load operates at less than full load for a majority of the time, installing ASDs will reduce energy consumption and save operating costs.

2.2.2. Fan motors in air handlers can account for 20 percent or more of energy usage in a commercial-type building. Energy costs of air distribution systems can be significantly decreased by converting constant volume systems to variable air volume (VAV) systems or by increasing the efficiency of existing VAV systems.

2.2.3. Good candidates for VAV conversion are constant volume systems with dual ducts or terminal reheat that use backward-inclined or airfoil fans. On existing VAV systems, convert airflow control from inlet vanes or outlet dampers to ASD control. Figure 2.1 shows the relative power consumption using outlet dampers, inlet vanes, or ASD control.

Figure 2.1. Variable Air Volume Systems Versus Power Output.



2.2.4. In many cases, energy savings can be realized simply by replacing older motors with newer energy efficient motors. But, further savings can often be obtained by evaluating the system needs and making an additional minor design change. For example, an exhaust system might be oversized. By using a smaller fan (and motor), a savings of 30 percent to 50 percent might be possible. By installing an ASD, a savings of 50 percent to over 80 percent might be possible. Energy efficiency improvement should be considered at the system level, not just the component (motor) level.

2.2.5. Chapter 3 provides specific guidance regarding energy savings analyses for motor upgrades and installations. Chapter 4 provides guidance for energy savings analyses for the application of ASDs.

Chapter 3

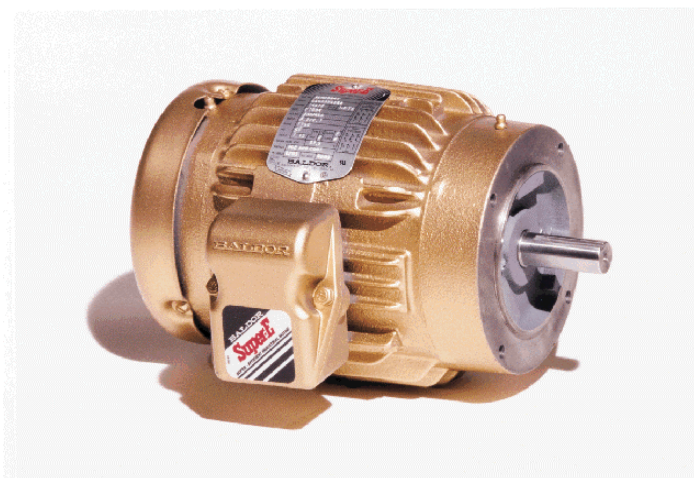
ENERGY EFFICIENT MOTORS

3.1. Energy Efficient Motor Design:

3.1.1. Introduction:

3.1.1.1. As part of converting electrical energy into mechanical energy, motors have several losses: electrical losses, iron (core) losses, mechanical (friction and windage) losses, and stray losses dependent on design and manufacturing. Energy efficient motors reduce energy losses through improved design, better materials, and improved manufacturing techniques. With proper installation, energy efficient motors can run cooler and consequently have higher effective service factors, longer bearing and insulation life, and less vibration. Energy efficient motors tend to last longer and can require less maintenance. By running cooler, bearing grease lasts longer, lengthening the required time between re-greasing. Lower operating temperatures also equate to longer lasting insulation; insulation life usually doubles for each 18 °F (10 °C) reduction in operating temperature.

Figure 3.1. Energy Efficient Motor.



3.1.1.2. Energy efficient motors are manufactured using the same frame as a standard T-frame motor, but have the following differences:

3.1.1.2.1. Higher quality and thinner steel laminations in the stator.

3.1.1.2.2. More copper in the windings.

3.1.1.2.3. Optimized air gap between the rotor and stator.

3.1.1.2.4. Reduced fan losses.

3.1.1.2.5. Closer matching tolerances.

3.1.1.2.6. A greater length.

3.1.1.3. An energy efficient motor produces the same shaft output power (horsepower), but uses less input power (kW) than a standard efficiency motor. Energy efficient motors must have nominal full load efficiencies that meet or exceed the National Electrical Manufacturers Association (NEMA) performance standards.

3.1.1.4. There are several opportunities for selecting an energy efficient motor for a particular installation, including when purchasing a motor for a new application, or considering rewinding of a failed motor, or evaluating the retrofit of an operable but inefficient motor to save energy. Energy efficient motors should be considered for the following applications:

3.1.1.4.1. For all new installations.

3.1.1.4.2. When major modifications are made to existing facilities or processes.

3.1.1.4.3. For all new purchases of equipment packages that contain electric motors, such as air conditioners, compressors, and filtration systems.

3.1.1.4.4. When purchasing spares or replacing failed motors.

3.1.1.4.5. In place of rewinding standard efficiency motors.

3.1.1.4.6. To replace grossly oversized and under loaded motors.

3.1.1.4.7. When an energy analysis indicates sufficient savings for an application.

3.1.2. NEMA Motor Standards:

3.1.2.1. NEMA MG 1, *Motors and Generators*, establishes standards for the construction and performance of motors. This document is the principal reference for motor design, construction and performance.

3.1.2.2. NEMA has assigned *Design* classifications that establish operating specifications for different motor types. The Design letter indicates the motor's torque characteristics and is an important motor selection consideration. Most induction motors are Design B, with Design A being the second most common type. Table 3.1 lists the key characteristics of NEMA Design B, C, and D motors. The Design A motor is a variation of the Design B motor and has a higher starting current and starting torque.

Table 3.1. NEMA Polyphase Motor Designs.

NEMA Design	Starting Current	Starting Torque	Breakdown Torque	Percent Slip
B	Medium	Medium	High	5% max
	Design B Applications: Normal starting torque for fans, blowers, rotary pumps, unloaded compressors, some conveyors, metal cutting machine tools, miscellaneous machinery. Slight speed change when changing load.			
C	Medium	High	Medium	5% max
	Design C Applications: High inertia starts, such as large centrifugal blowers, fly wheels, and crusher drums. Loaded starts, such as piston pumps, compressors, and conveyors. Slight speed change when changing load.			
D	Medium	Extra High	Low	5% or more
	Design D Applications: Very high inertia and loaded starts. Considerable variation in load speed.			

3.1.2.3. NEMA released specifications for a Design E motor in the October 1994 update to NEMA MG 1. The letter "E" was assigned because it is the next design to be standardized following the Design D motor, not because "E" stands for "efficiency". Nonetheless, the Design E specification has minimum efficiency values as one of its design requirements, specified in MG 1, Table 12-11. The Design E efficiency requirements are more stringent than for other motors designated as energy efficient. The Design E motor was specified to satisfy international standards developed by the International Electrotechnical Commission (IEC). IEC has a standard that is slightly less restrictive on torque and starting current than the Design B motor. This IEC standard allows designs to be optimized for higher efficiency. Design E motors can be used instead of Design A and B motors, with the following considerations:

3.1.2.3.1. For most moderate to high usage applications appropriate for a Design A or B motor, the Design E motor should usually be a better choice in terms of energy efficiency. But, there are slight performance differences between the designs. Design E locked rotor torque requirements are different from Design B. They are required to be somewhat higher than Design B levels for many motors under 20 horsepower and some motors over 200 horsepower, but are allowed to be lower for most motors from 20 horsepower to 200 horsepower. This means that a Design E replacement motor for an existing Design B motor should be evaluated carefully to ensure that it has sufficient torque to start when connected to its load.

3.1.2.3.2. Except for very small motors (under 3 horsepower), Design E motors are allowed to have considerably higher locked rotor (starting) current than Design B motors. (Note that Design A motors still have no upper limit whatsoever for their locked rotor current.) In the first ten milliseconds of starting, any motor's current can exceed the nominal locked rotor current. This momentary current spike is called "inrush" current and is likely to be highest of all in Design E motors. High inrush current can cause false trips by instantaneous trip units. As part of a Design E motor installation, the electrical protection should be reviewed to confirm that the motor will be able to start and accelerate to its full-load speed without tripping the associated electrical protection. In some cases, it might be necessary to replace the motor starter as part of the motor replacement.

3.1.2.3.3. Although the NEMA standard allows the same slip (up to 5 percent) for Designs A, B, and E motors, the range of actual slip of Design E motors is likely to be lower than for Designs A and B. This lower slip should be factored into savings calculations in retrofit situations for variable torque (such as pump and fan) applications.

3.1.3. Motor Efficiency Overview:

3.1.3.1. A standard motor is designed to ensure that its temperature rise requirements are satisfied in a cost-effective manner, with motor efficiency being a secondary consideration. To be considered energy efficient, a motor must meet performance criteria published by NEMA. An energy efficient motor has a nominal full-load efficiency rating that meets or exceeds the efficiency specified in NEMA MG1, Table 12-10. Manufacturers also sell motors with efficiencies significantly higher than the NEMA standard and use many terms to describe their most efficient motors, including adjectives such as *high*, *super*, *premium*, and *extra*, but there is no NEMA standard for any terminology other than *energy efficient*. These additional terms can create confusion when comparing motors. For this reason, always consult the nominal efficiency rating and the minimum efficiency rating. The nominal efficiency rating is the average efficiency of many motors of duplicate design. Even within a group of duplicate design motors, there is some variation in actual efficiencies due to variations in motor materials and manufacturing. For this reason, minimum efficiency ratings are also important and can be used as the basis for the manufacturer's guarantee. The minimum efficiency rating is sometimes referred to as the *guaranteed minimum efficiency*.

3.1.3.2. Motor efficiency is the ratio of the mechanical power output to the electrical power input:

$$Efficiency = \frac{Output}{Input} = \frac{Input - Losses}{Input} = \frac{Output}{Output + Losses}$$

3.1.3.3. Design changes and improved materials have reduced motor losses, making energy efficient motors more efficient than standard motors. Motor efficiency varies with several factors. Table 3.2 summarizes the factors that have the most effect on motor efficiency.

Table 3.2. Factors That Affect Motor Efficiency.

Factor	Effect	Range of Effect	Comments
Rated horsepower	Efficiency increases with horsepower	From less than 80% for 1 hp to over 97% for 500 hp	See Figure 3.2 for the efficiency as a function of horsepower; actual values vary with manufacturer and motor type.
Rated speed	A 4-pole motor is more efficient than a 2-pole or 6-pole motor	Several percent, depending on motor size	
Motor load	Efficiency is often near the maximum value at 75% load	Can vary by 5% to over 15% from 25% load to 125% load	Variation range decreases for larger motors. See Figure 3.3.
High efficiency versus standard efficiency	Standard efficiency motors are less efficient than high efficiency motors	Few percent	
Motor control by ASD	Motor efficiency and full load capability can be reduced by ASD non-sinusoidal output	About 1%	Varies with manufacturer.

Figure 3.2. Typical Full Load Motor Efficiency.

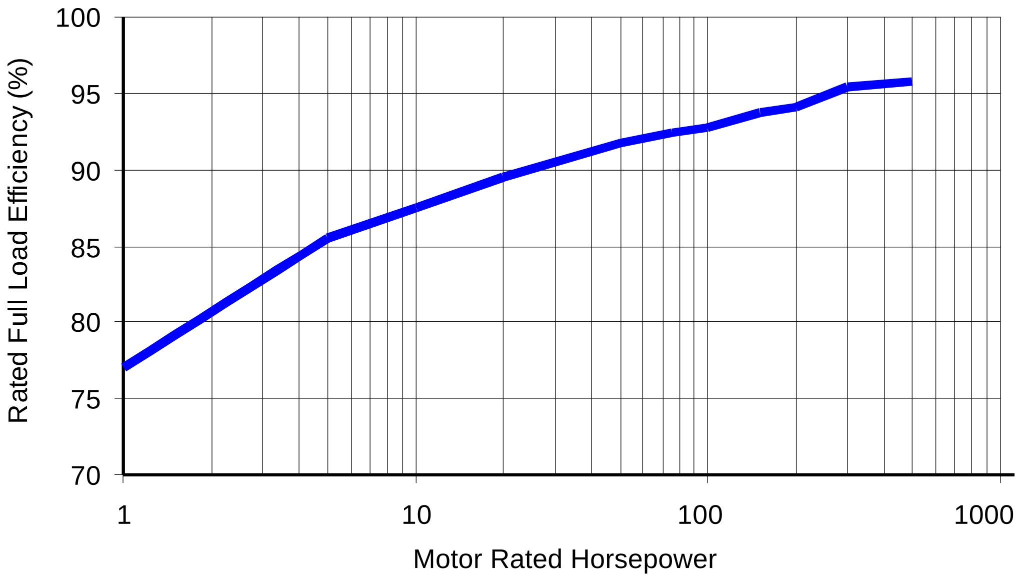
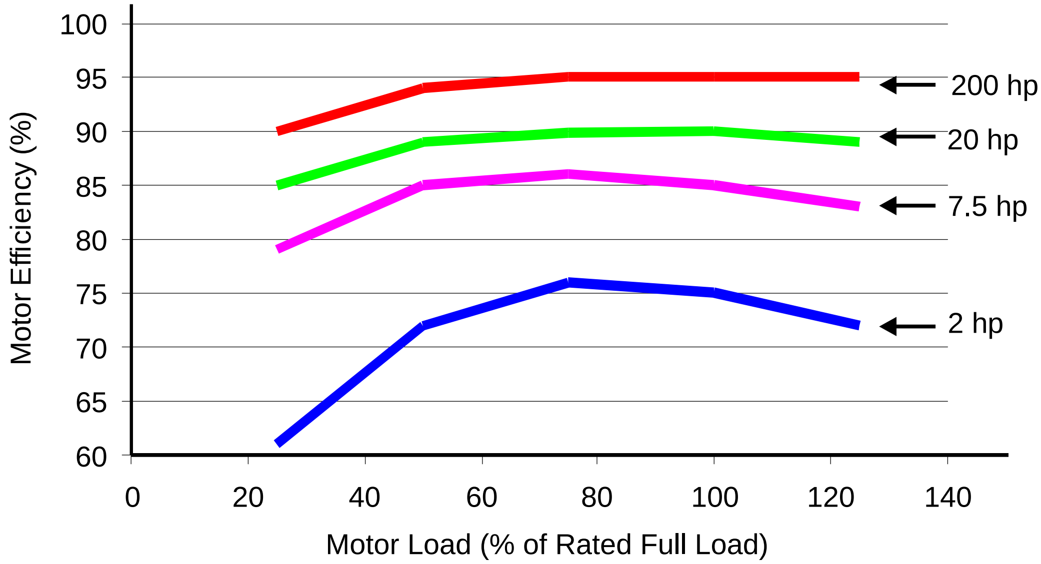


Figure 3.3. Typical Efficiency as a Function of Load.



3.1.3.4. Motor efficiency is identified on the motor nameplate by nominal efficiency, which represents the average efficiency of a large population of motors of the same design, and it is measured in accordance with NEMA MG 1, and IEEE 112, *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*, Test Method B. Table 3.3 provides the NEMA minimum required nominal efficiency for energy efficient motors as a function of horsepower rating. EPACT also specifies these values for motor sizes up to 200 horsepower. General purpose motors designated as energy efficient should not be available with a nominal efficiency less than listed in Table 3.3.

3.1.3.5. Motor manufacturers readily produce motors with nominal efficiency values better than required by NEMA and EPACT, and motor purchases should preferentially take advantage of the higher available efficiencies. Tables 3.4 and 3.5 provide the minimum recommended nominal full load motor efficiencies for open and enclosed designs, respectively. The values listed are for general purpose, single speed, polyphase induction motors. Some applications require definite purpose, special purpose, special frame, or special mounted polyphase induction motors; a motor meeting the recommended efficiency level is usually available for these applications also. The minimum recommended nominal full load motor efficiencies are readily achievable by motor manufacturers and these minimum values were obtained from *Buying Energy Efficient Products*, published by the Federal Energy Management Program. Tables 3.4 and 3.5 also provide the best available motor efficiencies for reference.

Table 3.3. NEMA and EPACT Full Load Nominal Efficiency Minimum Values.

Motor Size	Open Motors			Enclosed Motors		
(Horsepower)	1,200 rpm	1,800 rpm	3,600 rpm	1,200 rpm	1,800 rpm	3,600 rpm
1	80.0	82.5	—	80.0	82.5	75.5
1.5	84.0	84.0	82.5	85.5	84.0	82.5
2	85.5	84.0	84.0	86.5	84.0	84.0
3	86.5	86.5	84.0	87.5	87.5	85.5
5	87.5	87.5	85.5	87.5	87.5	87.5
7.5	88.5	88.5	87.5	89.5	89.5	88.5
10	90.2	89.5	88.5	89.5	89.5	89.5
15	90.2	91.0	89.5	90.2	91.0	90.2
20	91.0	91.0	90.2	90.2	91.0	90.2
25	91.7	91.7	91.0	91.7	92.4	91.0
30	92.4	92.4	91.0	91.7	92.4	91.0
40	93.0	93.0	91.7	93.0	93.0	91.7
50	93.0	93.0	92.4	93.0	93.0	92.4
60	93.6	93.6	93.0	93.6	93.6	93.0
75	93.6	94.1	93.0	93.6	94.1	93.0
100	94.1	94.1	93.0	94.1	94.5	93.6
125	94.1	94.5	93.6	94.1	94.5	94.5
150	94.5	95.0	93.6	95.0	95.0	94.5
200	94.5	95.0	94.5	95.0	95.0	95.0
250	95.4	95.4	94.5	95.0	95.0	95.4
300	95.4	95.4	95.0	95.0	95.4	95.4
350	95.4	95.4	95.0	95.0	95.4	95.4
400	—	95.4	95.4	—	95.4	95.4
450	—	95.8	95.8	—	95.4	95.4
500	—	95.8	95.8	—	95.8	95.4

Table 3.4. Nominal Full Load Percent Efficiency Recommendation—Open Drip Proof (OPD) Motors.

Motor Size	1,200 rpm		1,800 rpm		3,600 rpm	
(Horsepower)	Recommended	Best Available	Recommended	Best Available	Recommended	Best Available
1	82.5	82.5	85.5	86.5	80.0	84.0
1.5	86.5	87.5	86.5	86.5	85.5	86.5
2	87.5	88.5	86.5	88.5	86.5	86.5
3	89.5	90.2	89.5	90.2	86.5	87.5
5	89.5	90.2	89.5	90.2	89.5	91.0
7.5	91.7	91.7	91.0	91.7	89.5	90.2
10	91.7	92.4	91.7	91.7	90.2	91.7
15	92.4	92.4	93.0	93.0	91.0	91.7
20	92.4	93.0	93.0	93.6	92.4	93.0
25	93.0	93.6	93.6	94.1	93.0	93.0
30	93.6	93.6	94.1	94.1	93.0	94.0
40	94.1	94.5	94.1	94.5	93.6	94.5
50	94.1	94.5	94.5	95.0	93.6	94.1
60	95.0	95.4	95.0	95.4	94.1	94.5
75	95.0	95.8	95.0	95.4	94.5	95.4
100	95.0	95.4	95.4	95.8	94.5	95.8
125	95.4	95.8	95.4	95.8	95.0	95.4
150	95.8	95.8	95.8	96.2	95.4	96.2
200	95.4	96.2	95.8	96.2	95.4	96.2
250	95.4	95.8	96.2	96.2	95.8	95.8
300	95.4	95.8	95.0	96.2	95.4	96.2
350	94.5	96.2	95.4	96.2	95.0	96.2
400	94.1	96.2	95.8	96.5	95.0	96.2
450	94.5	96.2	95.4	95.8	95.4	96.2
500	94.5	96.2	94.5	95.8	94.5	96.5

Table 3.5. Nominal Full Load Percent Efficiency Recommendation—Totally Enclosed Fan Cooled (TEFC) Motors.

Motor Size	1,200 rpm		1,800 rpm		3,600 rpm	
(Horsepower)	Recommended	Best Available	Recommended	Best Available	Recommended	Best Available
1	82.5	85.5	85.5	86.5	78.5	80.4
1.5	87.5	87.5	86.5	87.5	85.5	87.5
2	88.5	88.5	86.5	86.5	86.5	87.5
3	89.5	90.2	89.5	89.5	88.5	89.5
5	89.5	90.2	89.5	90.2	89.5	89.5
7.5	91.7	91.7	91.7	91.7	91.0	91.7
10	91.7	92.4	91.7	91.7	91.7	91.7
15	92.4	92.4	92.4	93.0	91.7	91.7
20	92.4	93.0	93.0	93.6	92.4	92.4
25	93.0	93.0	93.6	94.1	93.0	93.6
30	93.6	93.6	93.6	94.5	93.0	93.6
40	94.1	94.5	94.1	94.5	93.6	94.1
50	94.1	94.5	94.5	95.0	94.1	94.1
60	94.5	95.0	95.0	95.4	94.1	94.5
75	95.0	95.0	95.4	95.4	94.5	95.0
100	95.4	95.4	95.4	95.4	95.0	95.8
125	95.4	95.8	95.4	96.2	95.4	95.8
150	95.8	96.2	95.8	96.2	95.4	96.2
200	95.8	95.8	96.2	96.5	95.8	96.2
250	95.6	95.8	96.2	96.5	95.9	96.5
300	95.4	96.2	96.1	96.5	95.8	96.2
350	94.5	95.0	96.2	96.3	94.8	95.8
400	94.5	95.0	95.8	96.2	94.5	95.8
450	94.5	95.4	94.5	95.0	94.5	95.4
500	94.5	95.4	94.5	95.4	94.5	95.4

3.1.3.6. Tables 3.4 and 3.5 can be used to determine if it is cost-effective to pay a premium for a higher efficiency motor. Determine the difference in energy usage cost for the various available motor efficiencies; this difference represents the potential cost-effectiveness of selecting a higher efficiency model, provided that the two motors have the same full load operating speed.

EXAMPLE: Assume a 50 horsepower, 1,800 rpm TEFC motor is available with the EPACT minimum required 93.0 percent efficiency and assume that the motor will operate full time (8,760 hours per year) and fully loaded to its nameplate rating. Determine if it is cost effective to purchase a motor at the Table 3.5 recommended efficiency level of ≥94.5 percent rather than at the EPACT minimum level. Assume the following:

Price of 93.0 percent efficiency motor: \$1,700
Price of 94.5 percent efficiency motor: \$2,200
Average electricity cost: \$0.06/kWh

For this example, the annual electricity usage and cost is given by:

$$Annual\ \ Energy\ Use\ (93\%\ efficient) = \frac{50\ hp \times 0.746\ \frac{kW}{hp} \times 8760\ hr}{0.93} = 351{,}342\ kWh$$

$$Annual\ \ Energy\ \ Cost = 351{,}342\ kWh \times \$0.06 / kWh = \$21{,}080$$

$$Annual\ \ Energy\ Use\ (94.5\%\ efficient) = \frac{50\ hp \times 0.746\ \frac{kW}{hp} \times 8760\ hr}{0.945} = 345{,}765\ kWh$$

$$Annual\ \ Energy\ \ Cost = 345{,}765\ kWh \times \$0.06 / kWh = \$20{,}746$$

The value of the annual energy savings provided by the higher efficiency motor is given by:

$$Annual\ \ Savings = \$21{,}080 - \$20{,}746 = \$334/year$$

The 94.5 percent efficiency motor costs approximately \$500 more than the 93.0 percent efficiency motor. The payback time for the purchase of the higher efficiency motor is given by:

$$Payback = \frac{\$500}{\$334/year} = 1.5\ \ years$$

3.1.3.7. Table 3.6 provides a summary of the above calculations and provides an equivalent example for a smaller 5 horsepower motor. The motor cost-effectiveness analysis is sensitive to the number of operating hours per year and the motor load factor. As the motor usage declines, the total energy used similarly declines, which reduces the potential cost savings differential. Paragraphs 3.2 through 3.2.10 discuss motor energy efficiency analyses in more detail.

Table 3.6. Motor Cost-Effectiveness Examples.

50 Horsepower (hp), 1,800 rpm		
Performance	Base Model	Recommended Level
Full Load Efficiency	93.0%	94.5%
Purchase Price	$1,700	$2,200
Annual Energy Use	351,342 kWh	345,765 kWh
Annual Energy Cost	$21,080	$20,746
Annual Energy Cost Savings	—	$334/year
Payback Time	—	1.5 years
5 Horsepower (hp), 1,800 rpm		
Performance	Base Model	Recommended Level
Full Load Efficiency	87.5%	89.5%
Purchase Price	$310	$380
Annual Energy Use	37,343 kWh	36,508 kWh
Annual Energy Cost	$2,241	$2,190
Annual Energy Cost Savings	—	$51/year
Payback Time	—	1.4 years

3.2. Motor Energy Efficiency Analysis:

3.2.1. The examples provided in Table 3.6 assume that the evaluated motors are fully loaded and operate continuously. Motors rarely operate at their full load point and often do not operate 100 percent of the time. Field tests of motors at various industrial plants indicate that, on the average, they operate at 60 percent of their rated load. Motors driving supply or return air fans in heating, ventilation and air conditioning (HVAC) systems often operate at 70 percent to 75 percent of rated load. Also, many motors are more efficient at 50 percent load than they are at full load.

3.2.2. The following information is required to complete an accurate assessment of energy savings for a particular energy efficient motor:

3.2.2.1. Load on the motor.

3.2.2.2. Operating efficiency of the motor at that load point.

3.2.2.3. Full load speed of the motor to be replaced.

3.2.2.4. Full load speed of the replacement motor.

3.2.2.5. Number of operating hours per year.

3.2.2.6. Electricity cost.

3.2.3. With the above information, the payback time can be calculated for motor alternatives. The following example illustrates the analysis process.

EXAMPLE: Compare the energy savings with a new energy efficient motor to the cost of a standard efficiency motor. The following information is provided for this example:

A 20 horsepower motor is needed.
Load factor (LF) is 75 percent.
The motor is operated approximately 6,000 hours per year.
The standard efficiency motor costs $850 and has an efficiency of 89 percent.
The energy efficient motor costs $1,050 and has an efficiency of 93 percent.
Local average electricity cost is $0.06/kWh.

The annual energy use is calculated below for each motor type:

$$Energy\ Use\ (89\%) = \frac{20\ hp \times 0.746\ \frac{kW}{hp} \times 6000\ hr \times 0.75\ LF}{0.89} = 75{,}438\ kWh/year$$

$$Energy\ Use\ (93\%) = \frac{20\ hp \times 0.746\ \frac{kW}{hp} \times 6000\ hr \times 0.75\ LF}{0.93} = 72{,}194\ kWh/year$$

3.2.4. Table 3.7 summarizes the results of the two motor types presented in the above example. Notice that the energy savings is several times the cost of the motor over the expected service life. And, the higher initial motor cost has paid for itself in just over one year.

Table 3.7. Energy Efficiency Analysis Example.

Parameter	Standard Efficiency Motor	Energy Efficient Motor
List Price for 20 Horsepower Motor	$850	$1,050
Efficiency	89%	93%
Use	6,000 hours/year	6,000 hours/year
Load Factor	75%	75%
Annual Energy Use	75,438 kWh	72,194 kWh
Annual Energy Savings	—	3,244 kWh
Value of Savings at $0.06/kWh	—	$195/year
Cost Difference Between Motors	—	$200
Payback Time	—	1.03 year

3.2.5. If energy savings are the sole reason for motor replacement, the new motor should have a nameplate full load speed equal to or slightly less than the motor being replaced, if possible. If such an energy efficient motor is not available, select the motor with the lowest full load speed (but same synchronous speed) that also provides the recommended minimum efficiency, or better. Energy efficient motors tend to operate at a speed slightly higher than standard efficiency motors; this higher speed increases the power consumption and can reduce the predicted energy savings if the cost savings are evaluated on the basis of efficiency alone. For example, variable air volume loads experience a power increase with the cube of the speed. Suppose the new energy efficient motor has a speed of 1,770 rpm and the old standard efficiency motor has a speed of 1,750 rpm. As shown below, the increase in power solely due to the speed increase is about 3.5 percent, which can substantially reduce the projected energy savings even though the new motor is energy efficient. Referring to the example shown in Table 3.7, a 3.5 percent increase in energy use with the higher efficiency motor would reduce the projected savings from $195/year to $43/year and the payback time would be extended to over 4 years.

$$\left(\frac{rpm_{new}}{rpm_{old}}\right)^3 = \left(\frac{1{,}770}{1{,}750}\right)^3 = 1.035, \ or\ a\ 3.5\%\ increase$$

3.2.6. As a general rule, motors that are undersized and overloaded have a reduced life expectancy with a greater probability of unanticipated downtime. Motors that are oversized and thus lightly loaded have an extended expected operating life, but can suffer both efficiency and power factor reduction penalties. Consider downsizing motors that are less than 40 percent to 50 percent loaded. But, downsizing should not be performed without an evaluation if the motor load factor exceeds 50 percent; there might be other design reasons for an oversized motor.

3.2.7. An inventory should be developed of all motors in each facility, beginning with the largest and those with the longest run times. This inventory enables informed choices about replacement, either before or after motor failure. Refer to Attachment 2 for guidance regarding the type of information needed for an inventory.

3.2.8. Field testing motors prior to failure can allow replacement motors to be properly sized to match the actual driven load. Motors that are significant energy users should head the inventory list. Motors that operate for extended periods of time and larger motors should also be on the list. Conversely, smaller motors that run intermittently should be placed toward the end of the list. Depending upon the size of the facility, it may be appropriate to list only motors that exceed minimum size and operating duration criteria. Each facility should establish appropriate thresholds. Selection criteria include:

3.2.8.1. 3-phase, NEMA Design B motors.

3.2.8.2. 10 to 600 horsepower.

3.2.8.3. At least 2,000 hours per year of operation.

3.2.8.4. Constant load (not intermittent, cyclic, or fluctuating).

3.2.8.5. Older and/or rewound standard efficiency motors.

3.2.8.6. Easy access.

3.2.8.7. A readable nameplate.

3.2.9. The objective is to sort through all the motors and rank order the list using size and annual operating time as the principal criteria. Once a short list of motors has been made, individual data collection can take place.

3.2.10. A motor energy analysis requires that information from the motor nameplate be obtained. A motor nameplate usually contains both descriptive and performance based data, such as full load efficiency, power factor, amperage, and operating speed. This information can be used to determine both the load imposed upon the motor by its driven equipment and the motor efficiency at its load point. Depending upon the motor age and manufacturer practices, not all of the desired information appears on every motor nameplate. It is not unusual for power factor and efficiency to be missing. When data is not available on the nameplate, contact the manufacturer for the missing information. The motor purchase date and its rewind history should also be recorded. The coupling type should be identified and the motor load (device being driven) described. Annual operating hours should be estimated by considering motor use on various shifts during work days, weekends, and holidays.

3.3. Motor Design Criteria:

3.3.1. Refer to AFMAN(I) 32-1181, for minimum design requirements. The guidance provided in this chapter supplements AFMAN(I) 32-1181.

3.3.2. Motors must be properly selected according to expected service conditions. Usual service conditions, as defined in NEMA MG 1, include:

3.3.2.1. Exposure to an ambient temperature between 32 °F (0 °C) and 104 °F (40 °C).

3.3.2.2. Installation in areas or enclosures that do not seriously interfere with the ventilation of the machine.

3.3.2.3. Operation within a tolerance of ± 10 percent of rated voltage.

3.3.2.4. Altitude not above 3,300 feet (1,006 meters). Table 3.8 provides the standard motor derating for operation above 3,300 feet (1,006 meters).

3.3.2.5. Operation within a tolerance of ± 5 percent of rated frequency.

3.3.2.6. Operation with a voltage unbalance of one percent or less. Paragraphs 5.3 through 5.3.7 discuss the effect of voltage and phase unbalance on motor operation.

Table 3.8. Motor Altitude Derating Factors.

Altitude Range (feet)	Altitude Range (meters)	Derating by Service Factor			
		1.0	1.15	1.25	1.35
3,300 – 9,000	1,006 – 2,743	93%	100%	100%	100%
9,000 – 9,900	2,743 – 3,018	91%	98%	100%	100%
9,900 – 13,200	3,018 – 4,023	86%	92%	98%	100%
13,200 – 16,500	4,023 – 5,029	79%	85%	91%	94%
Over 16,500	Over 5,029	Consult Manufacturer			

3.3.3. Operation under unusual service conditions can result in greater than expected efficiency losses and the consumption of additional energy. Both standard and energy efficient motors can have their efficiency and useful life reduced by abnormal service conditions.

3.3.4. Motors can lower the average power factor of the electrical system, which can result in penalty charges from the local utility. Refer to AFMAN(I) 32-1181 if power factor correction is to be considered.

3.3.5. The service factor is the percentage of extra demand that can be placed on a motor for short periods without damaging it. Service factors range from 1.00 (no overload capability) to 1.25 (25 percent overload capability), with higher service factors available. Select motors with a minimum 1.15 service factor and design for operation at 85 percent of the rated motor load, unless the motor has special design requirements. Note that a service factor greater than 1.0 is not intended to allow continuous overloading of a motor; it is intended to provide short-term capability for higher-than-expected loading.

3.3.6. Voltage at the motor terminals should be as close to the nameplate value as possible. Although motors are rated to operate within 10 percent of nameplate voltage, motor efficiency decreases as applied voltage decreases. When operating at less than 95 percent of nameplate voltage, motors lose 2 percent to 3 percent of rated efficiency. Also, operation at lower-than-rated voltage causes a higher temperature rise, which reduces insulation life.

3.3.7. Some motors have special voltage considerations or are designed for dual voltage ratings. Evaluate these motors carefully to ensure that design requirements are satisfied.

3.3.7.1. Dual Voltage Ratings. Some motors are supplied with dual voltage ratings. For example, a voltage rating of 230/460 indicates that the motor can be used in either 230 volt or 460 volt applications. If connected to a 460 volt source, the motor can operate within a balanced voltage of 460 volts ± 10 percent. If connected to a 230 volt source, the motor can operate within a balanced voltage of 230 volts ± 10 percent.

3.3.7.2. Wide-Range Voltage Ratings. If the motor nameplate shows a hyphen between two numbers, such as 208 – 230, the motor can operate properly for any voltage within this range including a +10 percent allowance on the high end and a -10 percent allowance on the low end. For example, the utilization voltage range for a motor rated at 208 – 230 volts is 188 to 253 volts if the 3-phase voltage supply is balanced.

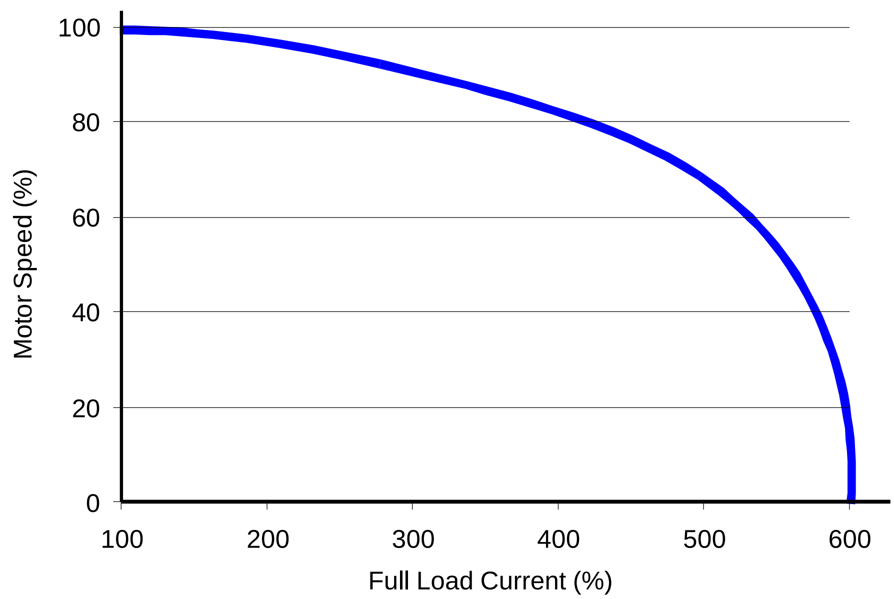
3.3.7.3. 230 Volt Motors on 208 Volt Systems. Do not use 230 volt motors on 208 volt systems because the utilization voltage will commonly be below the -10 percent tolerance on the voltage rating for which the motor is designed (a 230 volt motor is intended for use on a nominal 240 volt system).

3.4. Reduced Voltage Starting:

3.4.1. Full voltage starting is the least expensive and most efficient method of starting small motors. However, reduced voltage starting can be needed for large motors and for some small motor applications, primarily because the voltage drop caused by full voltage starting can interfere with other electrical equipment. An induction motor appears similar to a short circuit when it is started, drawing up to six times rated full load current, or more, for several seconds. Reduced voltage starting reduces the large current drawn during motor starting.

3.4.2. When a motor is first started, it is at rest. The current drawn during starting is high because the motor has no counter electromagnetic force (EMF) when first started. As the motor comes up to speed, counter EMF is developed in proportion to the speed, thereby causing the current to decrease (see Figure 3.4). Notice that the motor starting current tends to remain very high as a function of full load current until the motor is almost at full speed. Paragraphs 5.1 through 5.1.7 discuss other effects that can cause even higher transient current during motor starting.

Figure 3.4. Example Motor Starting Current as a Function of Motor Speed.



3.4.3. Internal motor heating is a function of the current. High motor starting current tends to cause a high heating rate during starting. Some motors have limits established on the number of consecutive starts that can be performed within a given time period because of the potential to cause insulation damage by overheating.

3.4.4. Reduced voltage starting reduces the motor starting current, which can improve electrical system operation. The reduced voltage drop helps avoid equipment operation problems and flicker can be reduced to acceptable levels. The following types of reduced voltage starting are commonly used:

3.4.4.1. Primary resistor starting.

3.4.4.2. Autotransformer starting.

3.4.4.3. Part-winding starting.

3.4.4.4. Wye-delta starting.

3.4.4.5. Solid-state starting.

3.4.4.6. ASD starting.

3.4.5. Refer to Attachment 3 for additional information regarding reduced voltage starting methods. Attachment 3 describes each method and explains the advantages and disadvantages of each method. ASDs are discussed in detail in Chapter 4. Because of the differences in electrical systems' design and motor applications, no single approach to reduced voltage starting is always preferred. Each application should be evaluated to determine the optimal design method. Manufacturers readily provide all of the reduced voltage starters described in Attachment 3.

3.5. Retrofit Design Criteria:

3.5.1. Some studies have concluded that most motors are significantly oversized. When a motor has a higher horsepower rating than is required by the load it is driving, the motor operates at part load. Motor efficiency drops rapidly when operation falls below 50 percent of full load capacity (see Figure 3.3). Also, power factor declines below 75 percent of full load, which means that lightly loaded motors can contribute to increased utility power factor charges. Oversized, under-loaded motors should be replaced with smaller energy efficient motors in most instances. A motor replacement analysis should be conducted for motors operating below 40 percent of their full load rating. Whenever a different size motor is installed in place of an existing motor, the electrical protection design must be evaluated to ensure that NEC electrical protection requirements continue to be satisfied; refer to Chapter 5 for guidance.

3.5.2. In retrofit designs, obtain an energy efficient motor with a speed closely matched to the speed of the existing motor. Induction motors have an operating speed that is slightly lower than their theoretical, or synchronous speed. For example, an 1,800 rpm motor might operate under full load at about 1,750 rpm. Energy efficient motors tend to operate at a slightly higher full load speed than standard motors (usually by about 5 to 10 rpm for 1,800 rpm motors). Centrifugal loads, like most pumps, fans, and compressors, will be affected by this higher speed; slightly more fluid or air will be delivered and energy consumption will increase by the cube of the speed increase (see paragraph 3.2.5 for an example).

3.5.3. Ensure that the selected replacement motor is appropriate for the application. For example, a NEMA Design B motor should not be selected to replace a NEMA Design C motor in a high torque application. In high-torque applications, NEMA Design A or Design B motors might trip the overload protection before the motor accelerates the load to its operating speed. Verify the NEMA design letter on the old motor as part of the replacement evaluation. Be careful not to mistake the motor insulation class code or kVA code letter for the NEMA design letter.

3.5.4. For most applications, NEMA Design E motors can be used instead of NEMA Design A or B motors. But the locked rotor torque and the locked rotor current should be evaluated to ensure that each Design E motor is able to start its load, and do so without tripping its associated electrical protection. Refer to paragraphs 3.1.2.3 through 3.1.2.3.3 for additional information regarding the Design E motor.

3.6. Rewinding and Repair:

3.6.1. Motor Failures:

3.6.1.1. Any motor will eventually fail. The following problems can lead to motor failure:

3.6.1.1.1. Insufficient lubrication—can cause bearings to fail.

3.6.1.1.2. Too much lubrication—excess grease can be forced into the motor past bearing seals and onto the motor windings where it can damage the insulation.

3.6.1.1.3. Improper lubrication—mixing incompatible greases can cause premature grease breakdown.

3.6.1.1.4. Contaminated grease—foreign particles can damage bearings.

3.6.1.1.5. Overvoltages—voltage spikes from lightning or switching transients can damage insulation.

3.6.1.1.6. ASD voltage spikes—ASDs can generate high-frequency voltage spikes that eventually damage the insulation, especially if cable lengths are long.

3.6.1.1.7. Harmonics and voltage unbalance—can contribute to motor overheating.

3.6.1.1.8. High operating temperatures—will contribute to insulation damage and can be caused by high ambient temperatures, motor overload, dirt in cooling passages, and operation at high altitudes.

3.6.1.1.9. Moisture—can cause motor damage and high humidity can cause problems if the motor is deenergized for long periods without space heaters.

3.6.2. Repair Versus Replacement Analysis:

3.6.2.1. When an existing motor fails, the following options are recommended:

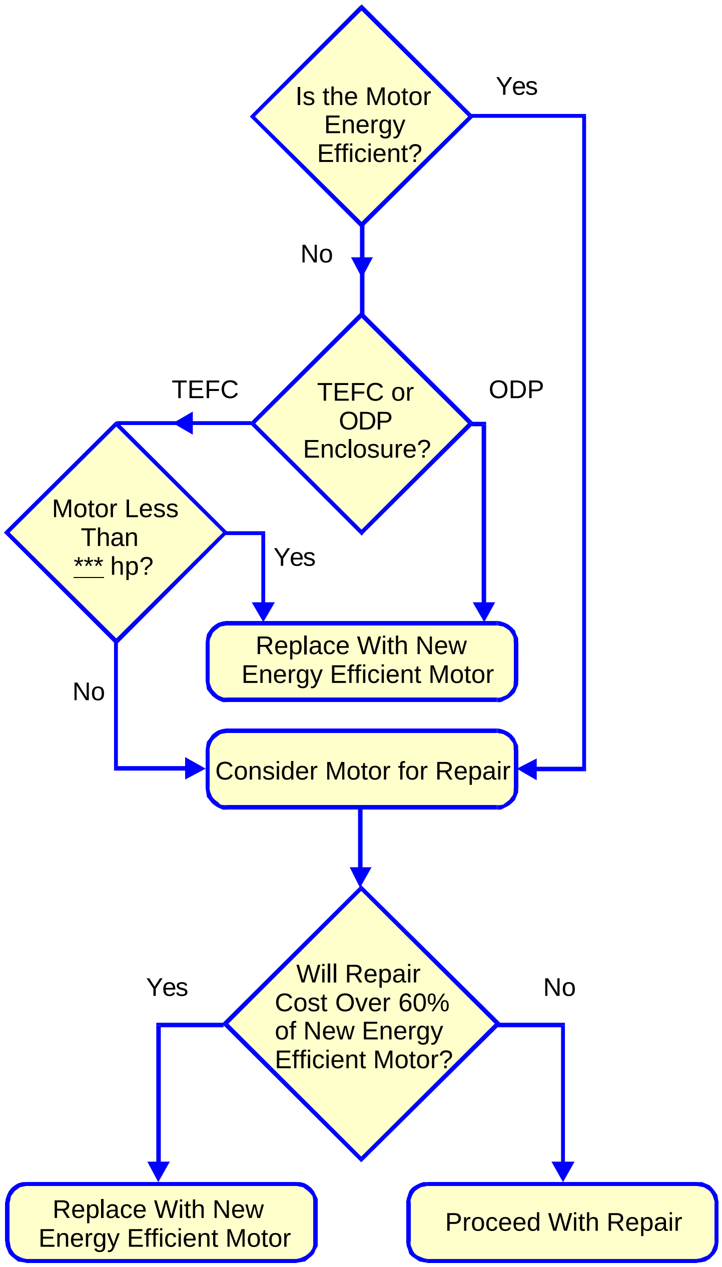
3.6.2.1.1. If the motor is already energy efficient, have it repaired. When an energy efficient motor requires repair, rewinding or repairing it at a quality repair shop will degrade its efficiency, but only slightly.

3.6.2.1.2. If it is an ODP motor, replace it with an energy efficient motor. It is usually not cost-effective to rewind ODP motors. Note: ODP refers to a motor enclosure design that allows outside air to blow directly through the motor, but has a cover that prevents drops of liquid from entering.

3.6.2.1.3. If it is a TEFC motor and is not energy efficient, replace it when it is smaller than the horsepower breakpoint. Otherwise send it out for repair. If the repair will cost more than 60 percent of a new energy efficient motor, replace the motor with a new energy efficient motor. Note: TEFC refers to a motor enclosure design that prevents outside air from flowing into the frame. Cooling of TEFC motors is provided by fins and a fan. TEFC motors are suitable for outdoor use, and in dusty or contaminated environments.

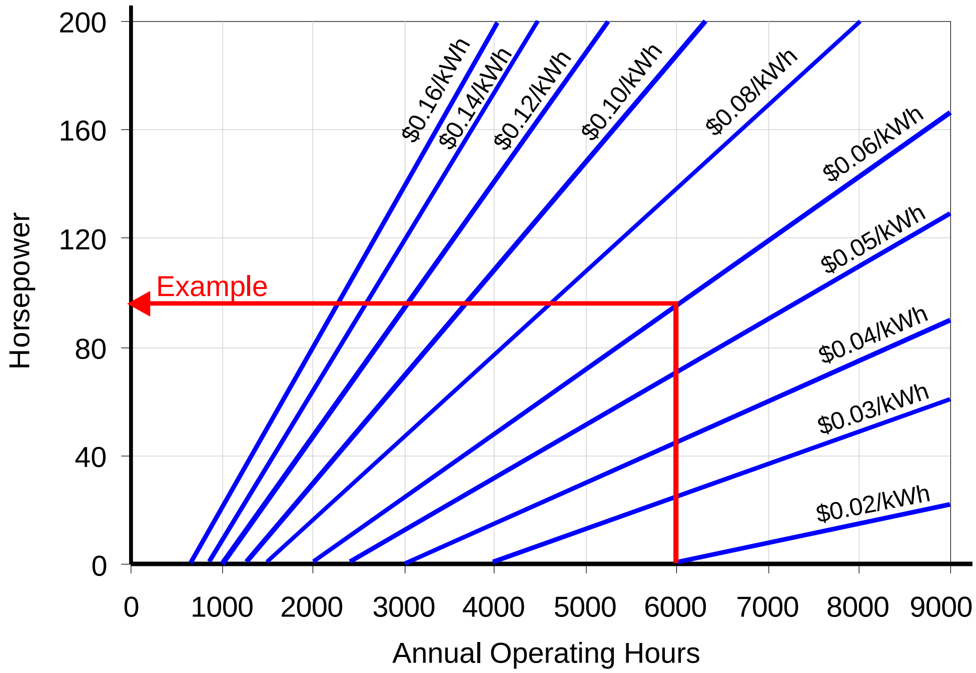
3.6.2.2. Figure 3.5 illustrates the repair or replacement evaluation process. In Figure 3.5, the question, "Motor Less Than *** hp?", refers to the minimum motor size below which it is more economical to replace it rather than repair it. Refer to paragraph 3.6.2.3 for additional information regarding how to determine this motor size.

Figure 3.5. Repair Versus Replacement Flow Chart.



3.6.2.3. Figure 3.6 shows how to determine the horsepower breakpoint as a function of local electricity cost (the term *breakpoint* refers to the motor size below which it is more economical to replace the motor than repair it). This figure is adapted from the *Industrial Electrotechnology Laboratory Horsepower Bulletin*, available from the DOE Motor Challenge Program Information Clearinghouse at PO Box 43171, Olympia, Washington, 98504-3171 or by telephone at 800-862-2086. Refer to this bulletin for details regarding assumptions for the various breakpoints. But, Figure 3.6 will be adequate for most situations.

Figure 3.6. TEFC Motor Replacement Decision Chart.



EXAMPLE: Assume the average cost of electricity is $0.06/kWh and the motors of interest operate for a minimum of 6,000 hours per year. Figure 3.6 shows the recommended horsepower breakpoint (shown in red). Motors smaller than 100 horsepower should be replaced rather than repaired.

3.6.2.4. As part of a repair versus replacement evaluation, verify that the new motor has the same frame design as the old motor. If a new frame size is provided, additional effort will be necessary to complete the installation.

3.6.2.5. For specific evaluations, MotorMaster® can be used to determine whether repair or replacement is the best alternative. Refer to paragraphs 3.7.3 through 3.7.3.2 for additional information regarding a MotorMaster® analysis.

3.6.3. Motor Repair Guidelines:

3.6.3.1. The *Electric Motor Model Repair Specifications* manual is recommended as a reference for motor repair and rewinding. It is based in part on the Electric Apparatus Service Association (EASA) *Standards for the Repair of Electrical Apparatus*. Background information regarding motor repair is provided in *Industrial Motor Repair in the United States* and *Quality Electric Motor Repair: A Guidebook for Electric Utilities*. All of these documents are available from the DOE Motor Challenge Program Information Clearinghouse at PO Box 43171, Olympia, Washington, 98504-3171 or by telephone at 800-862-2086.

3.6.3.2. Improper motor repair will lead to early motor failure also. The following problems have occurred with motor repair:

3.6.3.2.1. Errors in the winding pattern, substitution of smaller gauge wire, or changes in number of turns, which tend to increase motor losses, thereby causing a higher operating temperature.

3.6.3.2.2. Excessive vibration can occur during operation if an out-of-balance rotor or bent shaft are not corrected before reassembly.

3.6.3.2.3. Poor impregnation of varnish can cause poor heat transfer or winding motion under magnetic forces.

3.6.3.2.4. Poorly restrained end turns can cause acoustic vibration when powered from an ASD.

3.6.3.3. The following guidelines are recommended to ensure a quality motor repair:

3.6.3.3.1. Ensure the original design is duplicated by the repair with regard to number of turns; winding design and coil configuration; wire cross sectional area; and rolling bearing size, type, and specification including seals and shielding, if applicable.

3.6.3.3.2. Replace bearings as part of the rewind. Almost half of motor failures involve bearing failures.

3.6.3.3.3. Record core loss before and after stripping.

3.6.3.3.4. Repair or replace defective laminations.

3.6.3.3.5. Measure and record winding resistance, no-load amperes, voltage, and no-load watts.

3.6.3.4. The following repair practices are not recommended:

3.6.3.4.1. Heating of stators above 650 °F (343 °C).

3.6.3.4.2. Sandblasting of iron core.

3.6.3.4.3. Knurling, painting, or peening bearing fits.

3.6.3.4.4. Stripping with an open flame.

3.6.3.4.5. Grinding laminations or filing slots.

3.6.3.4.6. Increasing the air gap.

3.6.3.4.7. Increasing the stator winding resistance.

3.6.3.4.8. Changing the winding design.

3.6.3.4.9. Modifying the motor mechanical design without approval.

3.6.3.5. The repair shop should be capable of performing a high quality repair or rewind service. To asses repair shop capability, recommend checking for:

3.6.3.5.1. Implementation of EASA Q, International Standards Organization (ISO) 9000, or other quality assurance program.

3.6.3.5.2. Procedures in place conforming to EASA guidance.

3.6.3.5.3. Test equipment available and calibrated at specific periodic intervals, such as annually.

3.6.3.5.4. Variety and adequate quantity of wire sizes and shapes in stock.

3.6.3.5.5. Neat and organized facility with knowledgeable personnel.

3.6.3.5.6. Maintenance records for all repairs.

3.7. MotorMaster® Evaluations:

3.7.1. Introduction to MotorMaster®:

3.7.1.1. MotorMaster® is a software program designed to support a motor management program. MotorMaster® has received wide industry acceptance and is the preferred tool for managing and evaluating motors at each facility.

3.7.1.2. MotorMaster® is available from the DOE Motor Challenge Information Clearinghouse at PO Box 43171, Olympia, Washington, 98504-3171, and it can be ordered by telephone at 1-800-862-2086.

3.7.1.3. MotorMaster® provides the following features:

3.7.1.3.1. It contains a database of over 10,000 NEMA Design B 3-phase motors. The motors range from 1 to 600 horsepower, with standard speeds from 900 to 3,600 rpm. Different motor enclosures types are supported, including ODP, TEFC, TENV, and EXPL.

3.7.1.3.2. Technical data is contained to facilitate motor evaluations, including part load efficiency, power factor, full load speed, torque, and voltage.

3.7.1.3.3. Purchase information is provided for the database motors, including list price, warranty, catalog number, and manufacturer’s address.

3.7.1.3.4. Analysis features calculate energy savings, dollar savings, simple payback, cash flows, and after tax rate of return on investment associated with selecting an energy efficient motor for an application.

3.7.1.3.5. It is designed to store and manage information regarding the motor inventory at each facility, including nameplate information and field measurement data.

3.7.1.4. Figure 3.7 shows the MotorMaster® startup screen providing various options. The keys of most interest in Figure 3.7 are provided in Figure 3.8.

Figure 3.7. MotorMaster® Startup Screen.

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Figure 3.8. MotorMaster® Functions.

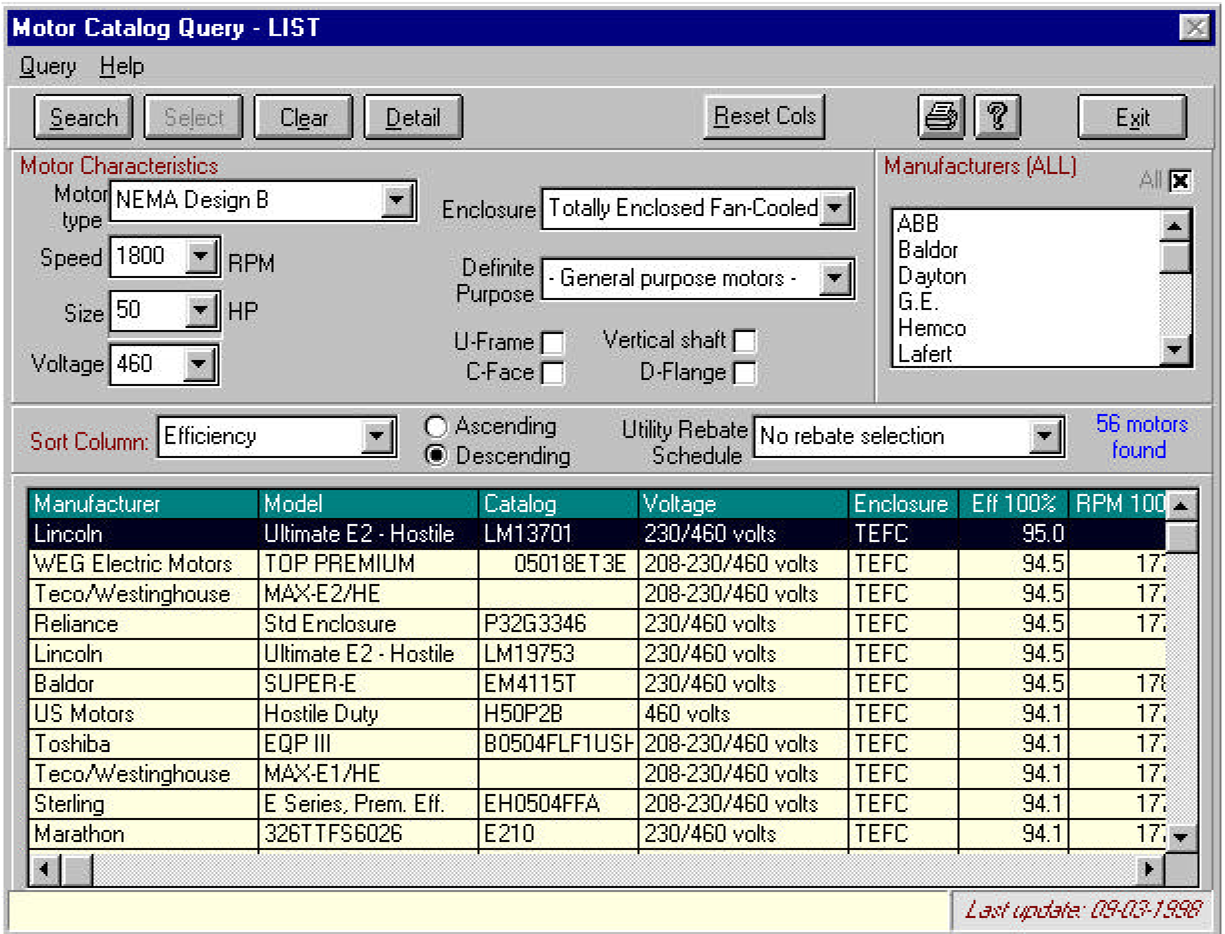
Key	Description
List	Create a list of available new motors that meet the required purchase specifications.
Compare	Determine both energy and dollar savings due to selecting and operating an energy efficient motor model.
Life Cycle	Compute annual cash flows and the after tax rate of return on a motor systems investment.
Inventory	Create the facility or base motor inventory database and generate searches and reports based on motor and load descriptors.
Batch Analysis	Initiate motor repair or replacement analyses for populations of motors at a facility or base.

3.7.1.5. The *MotorMaster User Guide* provides a detailed description of the various capabilities and application of MotorMaster®.

3.7.2. MotorMaster® Database:

3.7.2.1. MotorMaster® contains a database of over 10,000 motors. The database can be searched for motors of a particular type, speed, horsepower rating, voltage, enclosure, and application. All motors with the selected search attributes will be listed. The motors can be displayed sorted by efficiency as shown in Figure 3.9, or can be sorted by manufacturer, full load rpm, power factor, list price, or locked rotor torque.

Figure 3.9. Typical Motor Listing.



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3.7.2.2. The database can be used to evaluate different motor options. For example, different motors can be compared to determine if a motor with higher efficiency provides adequate savings to justify a possibly higher list price. Figure 3.10 shows an example comparison between two motors with efficiencies of 92 percent and 94.5 percent, respectively. Notice that a utility rate schedule is selected to develop the operating cost of each motor. The hours of use per year are entered by the user and the motor list price is obtained from the MotorMaster® database. Figure 3.11 shows that the higher initial cost of the higher efficiency motor is paid back within 1.88 years. MotorMaster® performs this calculation automatically.

Figure 3.10. Comparison of New Motor Options.

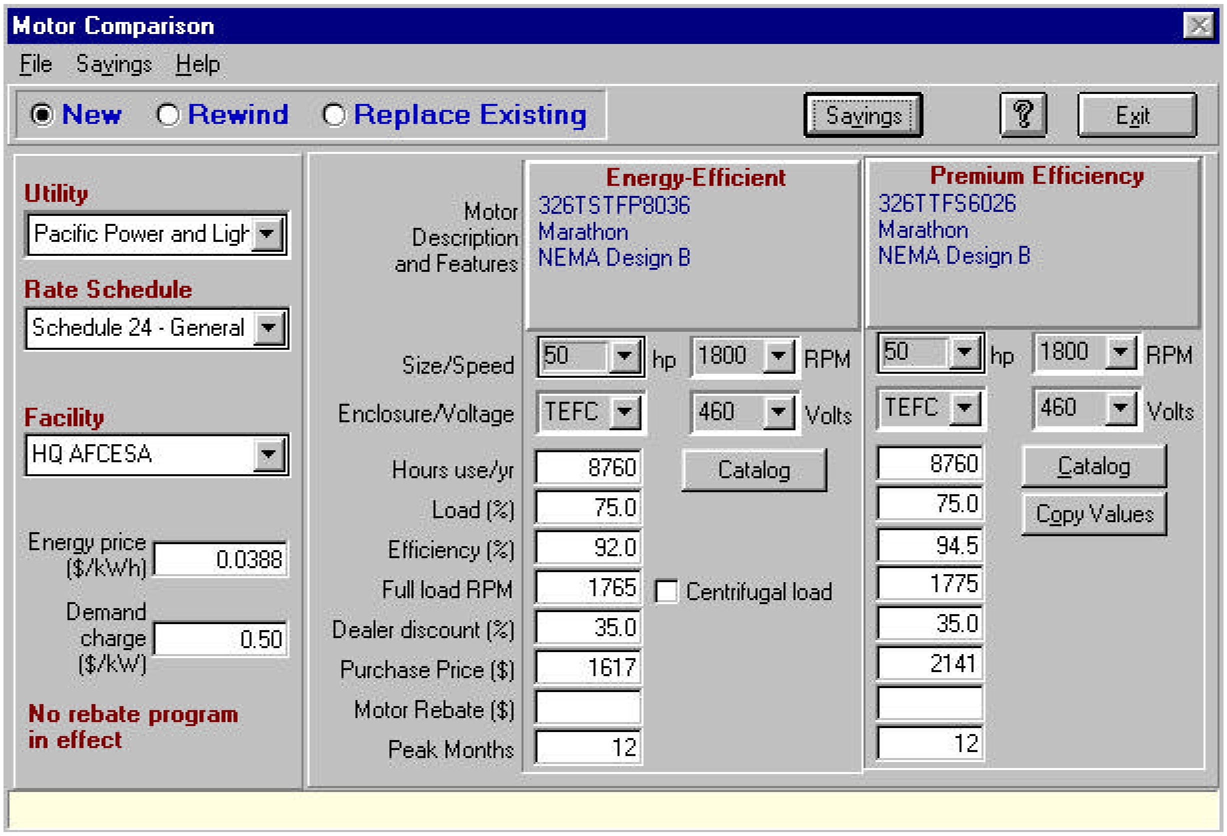

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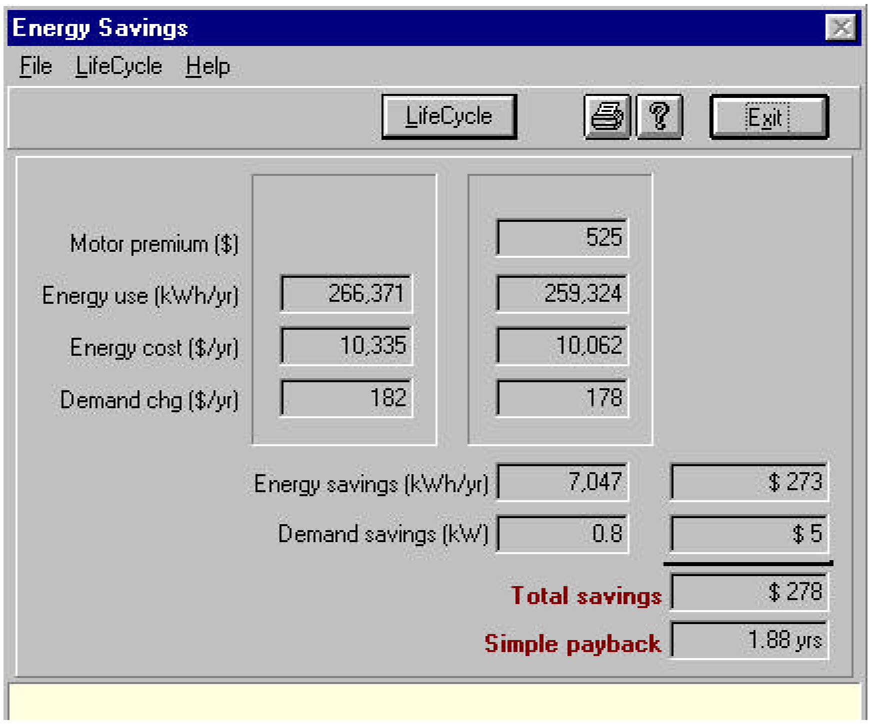
Figure 3.11. New Motor Comparison Cost Savings Summary.



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3.7.3. MotorMaster® Repair Versus Replacement Evaluations:

3.7.3.1. Paragraphs 3.6 through 3.6.3.5.6 provide specific guidance regarding motor repairs. MotorMaster® supports a rewind or replace decision by comparing the cost of a rewind to the cost of a replacement motor. Figure 3.12 shows the MotorMaster® entry screen. The motor to be rewound can be manually entered or can be retrieved from the inventory list. The MotorMaster® database is used to select the desired replacement motor. The new motor will have a higher efficiency and will save energy compared to the rewound motor. Based on the expected replacement motor price and the cost of electricity, MotorMaster® then calculates the payback time for the replacement motor to break even with the rewound motor. Figure 3.13 shows a sample MotorMaster® calculation.

Figure 3.12. Rewind Versus Replace Evaluation.

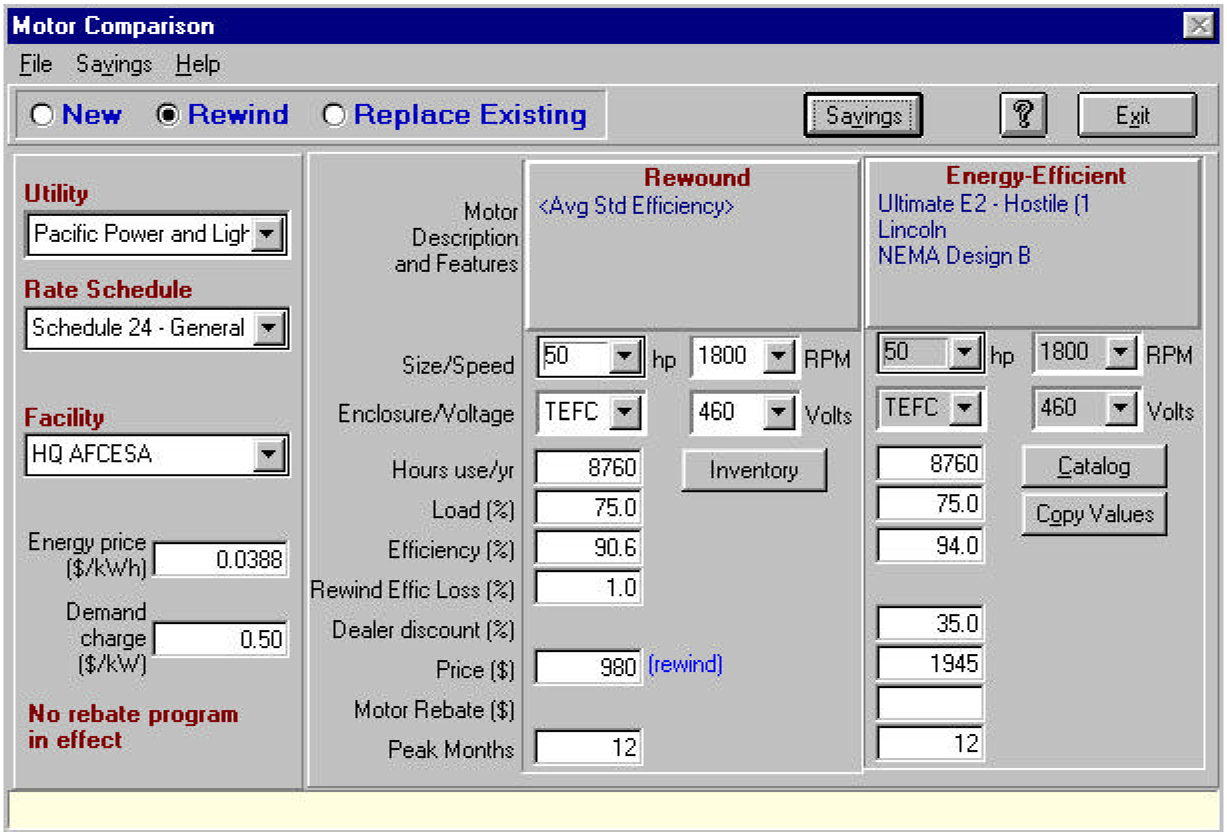

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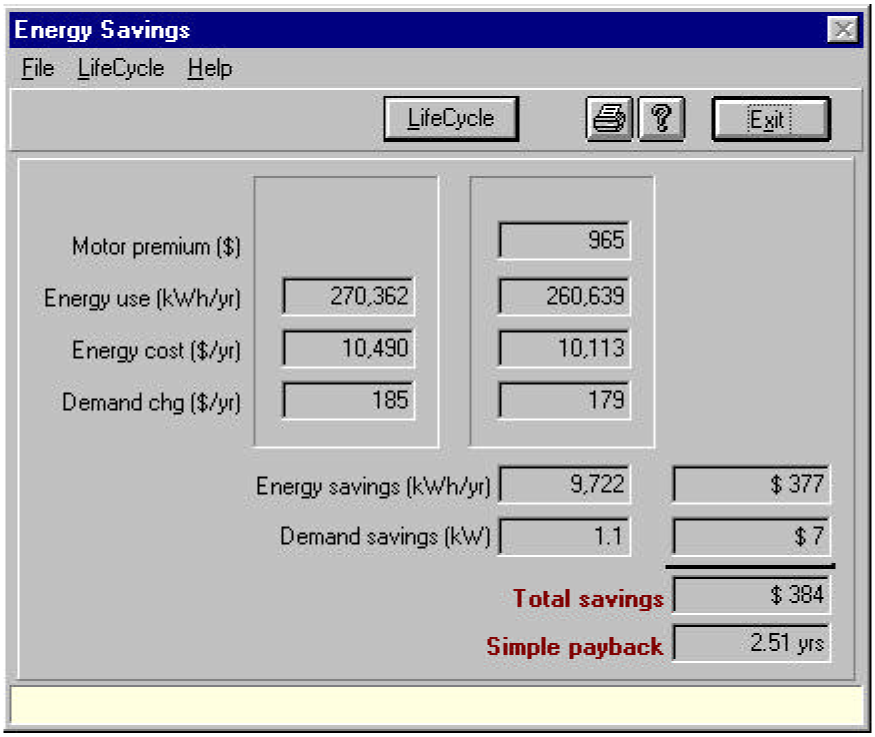
Figure 3.13. Example Payback of Replace Versus Rewind Evaluation.



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3.7.3.2. MotorMaster® has many other features that are important to a motor management program. Some of the key features have been described here to introduce MotorMaster® and to show by example how MotorMaster® can simplify motor analyses. Refer to the *MotorMaster User Guide* for additional information.

Chapter 4

ADJUSTABLE SPEED DRIVES

4.1. Introduction:

4.1.1. Adjustable speed drives (ASDs) are electronic controllers that vary the speed of motors. ASDs save substantial energy when applied to variable torque loads and the application of ASDs will result in a reduction in electricity consumption in most facilities. Other potential benefits include improved process control, reduced mechanical stress by soft start capability, and improved electrical system power factor.

4.1.2. The guidance provided in this chapter will not result in the least expensive design. Although ASDs can provide significant energy savings and operational improvements, numerous problems have also occurred with ASD installations. Common problems have been addressed in this chapter by ensuring that ASDs are properly designed to be reliable under a variety of operating conditions. And, potential ASD interactions with the rest of the electrical system have been considered. In summary, the energy savings that can be realized with ASD installations should not be obtained at the expense of a less reliable electrical system. For this reason, ASD design guidance in this chapter addresses issues well beyond energy efficiency.

4.1.3. ASDs take a 50 hz or 60 hz ac input and generate a variable frequency output to control the speed of the motor as necessary to meet the load demand. Figure 4.1 shows a simplified layout of an ASD. The rectifier converts the incoming ac power to a dc output. The dc link further reduces any ripple in the rectifier output. The inverter circuit converts its dc input into a variable frequency ac voltage to control the speed of an induction motor. Figure 4.2 shows a typical ASD.

Figure 4.1. ASD Internal Configuration.

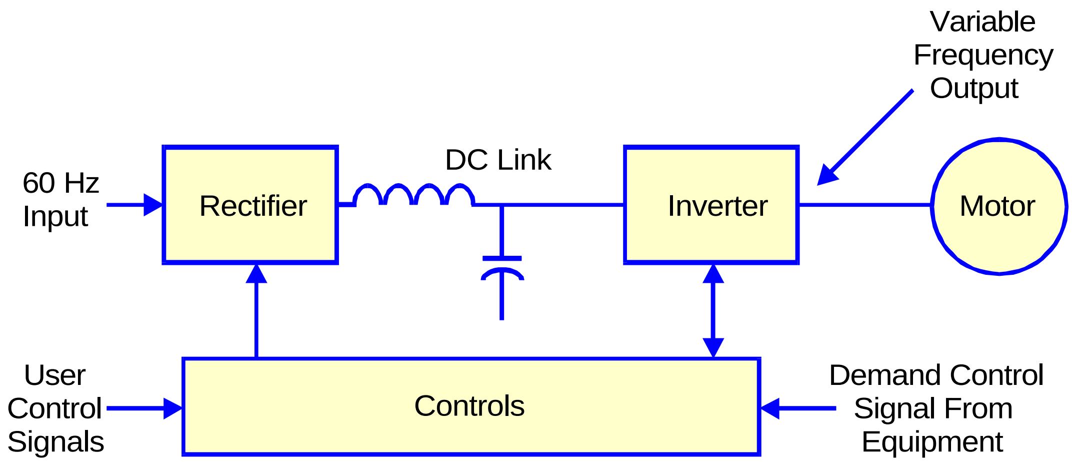
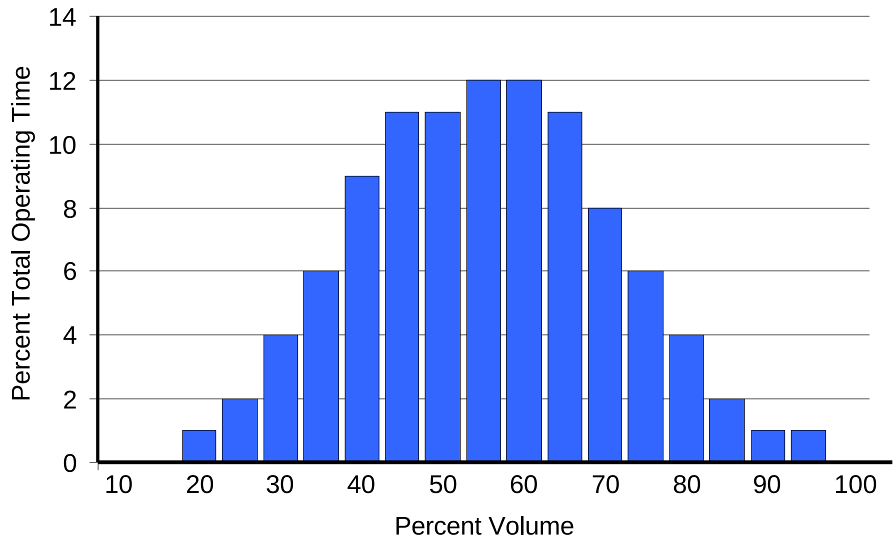


Figure 4.2. Typical ASD.

4.1.4. The best applications for ASDs are large motors that can operate for many hours each year at reduced speeds. Variable flow applications with throttling or bypass devices to modulate flow are good candidates for ASDs. Potential applications include centrifugal fans, pumps (centrifugal, propeller, turbine), agitators, and axial compressors. If HVAC fans have inlet vanes or outlet dampers to throttle full air output in variable air volume (VAV) systems, these dampers or vanes can usually be removed or disabled and retrofitted with ASDs. Circulation pumps for chilled water often have throttling or bypass valves that can be retrofitted with ASDs.

4.1.5. Energy savings are possible with variable torque loads, such as fans and pumps, because torque varies as the square of the speed, and horsepower varies as the cube of speed. For example, if fan speed is reduced by 20 percent, motor horsepower (and energy consumption) is reduced by 50 percent. If fan speed can be reduced by 50 percent, the power requirement is only 12.5 percent of the full-speed value, or an energy savings of almost 90 percent. Figure 4.3 shows a common operating history for a centrifugal fan in a VAV system. As can be seen in this example, the system operates at 70 percent volume or below almost 90 percent of the time. In a case such as this, an ASD can provide a significant energy savings.

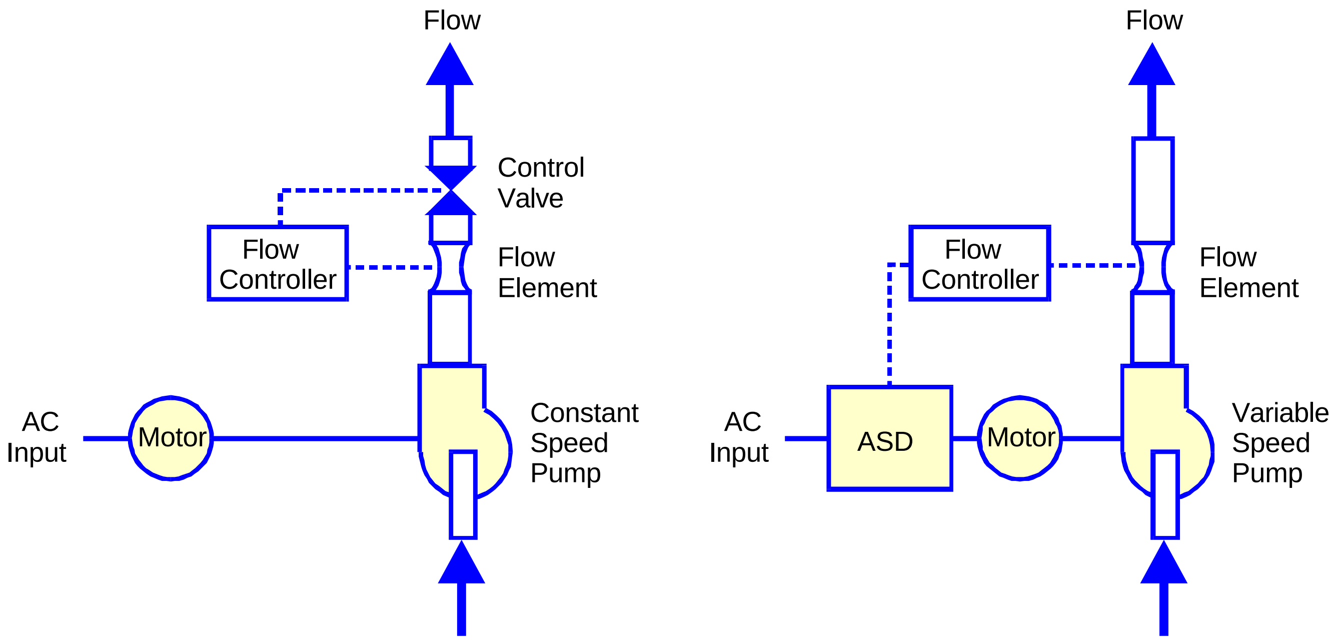
Figure 4.3. Sample Operating History for a Centrifugal Fan in a VAV System.



4.1.6. ASDs can be retrofitted into existing motor systems, and can operate both standard and high efficiency motors ranging in size from less than one horsepower to several thousand horsepower. Unlike mechanical and hydraulic motor controllers, ASDs can be located remotely (within limits) and do not require mechanical coupling between the motor and the load. This simplifies installation and alignment of motor systems.

4.1.7. The installation of an ASD involves some change in the process control method. Figure 4.4 shows a simplified example of a water flow system in which a flow element measures water flow and a flow controller uses the flow signal to adjust the flow control valve position and control the flow rate. With the installation of an ASD, the control valve is removed (or fully opened) and the flow signal is sent to the ASD, which then controls the motor speed to maintain the desired flow rate.

Figure 4.4. Flow Control With an ASD.



4.1.8. ASD installations can also solve ongoing maintenance problems. For example, one hospital used a unique inlet vane design for HVAC flow control. Because of their unique design, repair or replacement of the inlet vanes tended to be relatively expensive. By installing ASDs, the inlet vanes were locked in the fully open position and the associated maintenance expense was avoided in the future. ASDs can also be used for motor soft starts to reduce the stress on the connected load or to reduce the motor starting current.

4.2. Design Criteria. Refer to AFMAN(I) 32-1181 for minimum design requirements. The guidance provided in this chapter supplements AFMAN(I) 32-1181.

4.2.1. ASD Designs:

4.2.1.1. Although there are other types, two types of ASD designs are most commonly used: variable source inverter (VSI), and current source inverter (CSI).

4.2.1.2. VSI designs use pulse width modulation (PWM) to generate the output waveform. PWM is the dominant ASD design technology in the ≤1 horsepower to 500 horsepower range because of its reliability, affordability, and availability. PWM outputs emulate sinusoidal power waves by varying the width of the pulses in each half cycle. Advantages of PWMs are low harmonic motor heating, excellent input displacement power factor, high efficiency of 92 percent to 96 percent, and the ability to control multiple motor systems with a single drive.

4.2.1.3. CSI designs are also reliable because of their inherent current-limiting characteristics and simple circuitry. CSIs have regenerative power capabilities, meaning that CSI drives can reverse the power flow back from the motor through the drive. Unfortunately, CSIs reflect large amounts of power harmonics back to the source, have poor input power factors, and can produce jerky motor operations (cogging) at very low speeds. CSIs are usually used for large (over 300 horsepower) induction and synchronous motors.

4.2.2. Motor Design Considerations for ASDs:

4.2.2.1. At the rated full load of the driven equipment, the output voltage and frequency of the ASD should be the same as the motor's rating. Note that this design recommendation also places limits on the motor design; the motor should not have a significantly higher full load horsepower or speed rating than the driven load. Mismatches can easily cause operational problems, including efficiency losses and increased ASD input current. In extreme cases, a mismatch can cause the ASD to trip on overcurrent during motor starting or cause the ASD input current to be substantially higher than the design without the ASD.

4.2.2.2. The ASD short term current rating should be adequate to produce the required motor starting torque, including loads with high starting torque. Inappropriate designs, such as using an 1,800 rpm motor at reduced speed to drive an 870 rpm load can cause the ASD to exceed its short term current rating.

4.2.2.3. Motors can overheat at the lower operating speed set by an ASD and, in some cases, they can overheat even at full load/full speed operation because of the ASD's non-sinusoidal output. On fan-cooled motors, decreasing the motor's shaft speed by 50 percent decreases the fan's cooling effects proportionately. If the motor is fully loaded and speed decreases, the motor must supply full torque with reduced cooling. In extreme cases, this can cause the motor insulation to fail or can reduce the motor life. For many applications, the load will be well less than full load and the motor will be able to operate at reduced speed without overheating.

4.2.2.4. The motor should have a minimum 1.15 service factor or be rated well above the actual load it will be carrying. Verify with the manufacturer that the motor is capable of acceptable operation with an ASD. Standard motors can often operate down to 50 percent of rated speed, high efficiency motors can often operate down to 20 percent of rated speed, and "inverter duty" motors can operate below 20 percent of rated speed without problems in a variable load application. Motors designed specifically for ASD operation usually incorporate special cooling provisions and may use a higher class insulation.

4.2.3. Power Quality:

4.2.3.1. Harmonic Distortion. Ensure that the final installation complies with IEEE 519 regarding harmonic distortion limits (refer to AFMAN(I) 32-1181, Chapter 8, for an explanation of harmonic distortion limits). The amount of harmonic current distortion generated by the ASD depends on the ASD design and the ASD filter design. Some ASD manufacturers provide software to assist with a harmonic distortion evaluation. Power quality field measurements should be taken after the installation is complete to confirm that the system total harmonic distortion is not degraded beyond acceptable levels. If the ASD can be provided power from a standby generator upon loss of normal commercial power, the harmonic distortion evaluation must include the system effects when the standby generator is the power source. Refer to paragraphs 4.3.5 through 4.3.5.5 for additional guidance regarding harmonic distortion.

4.2.3.2. Voltage sags can cause nuisance tripping. The ASD should be protected against undesired tripping on momentary voltage sags or short duration voltage losses. Refer to paragraphs 4.3.2 through 4.3.2.3.2 for additional information.

4.2.3.3. Nearby capacitor switching can cause transient overvoltages, resulting in nuisance tripping. In this case, ensure the ASD either has input filtering to reduce the overvoltage or has automatic reset circuitry.

4.2.3.4. Medium voltage motor applications should be carefully evaluated to verify that the selected design will not degrade power quality below acceptable levels. ASD designs for medium voltage applications often generate a larger proportion of harmonic distortion.

4.2.4. Bypass Operation:

4.2.4.1. Important applications should include bypass operation capability to allow motor operation independent of the ASD. Some applications require bypass so that the motor can always be operated, such as for heating and cooling of a communications or computer room. More commonly, bypass ability is provided to enable continued motor operation in the event of ASD failure. Fire and safety requirements might necessitate a bypass to ensure the evacuation of smoke from a building after a fire.

4.2.4.2. Bypass capability can be accomplished by a manual transfer switch or by magnetic contactors. Figures 4.5 and 4.6 show the two types of configurations. More complex transfer schemes are usually not cost-effective. Manual transfer is used in applications in which short term loss of the motor is acceptable, followed by manual action to restore power to the motor. The use of magnetic contactors allows remote operation of the bypass and can include auxiliary contacts to operate the bypass on loss of the ASD.

Figure 4.5. Manual Transfer Bypass.

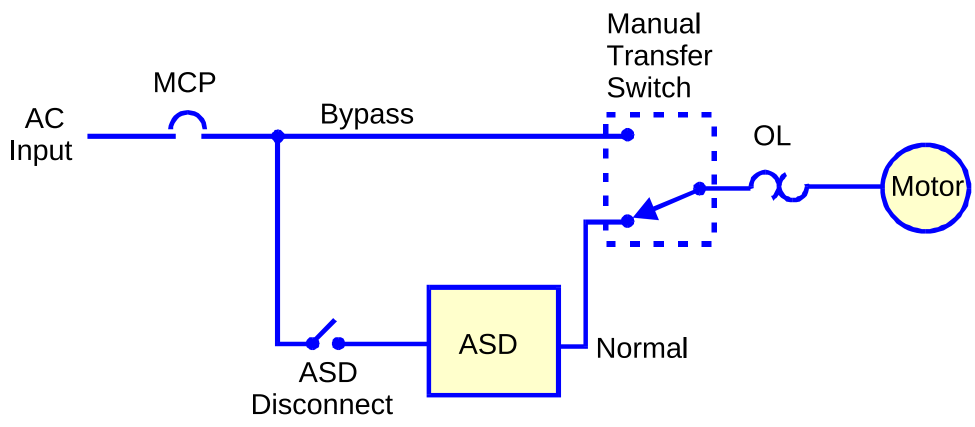
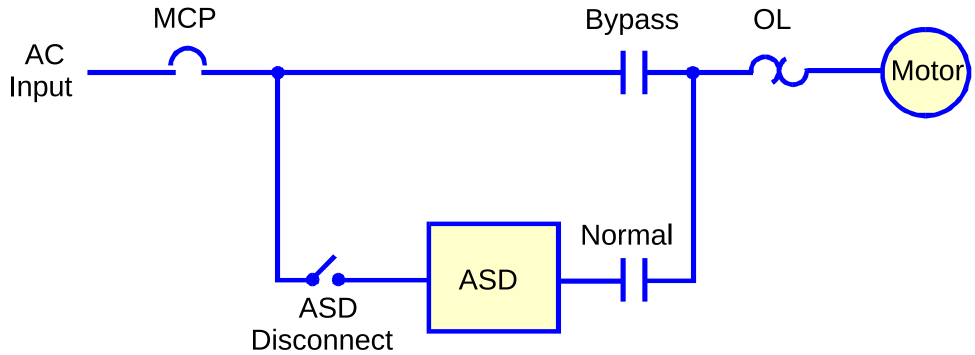


Figure 4.6. Bypass by Magnetic Contactors.



4.2.4.3. The manual transfer switch is the least expensive option and is acceptable for many applications. Regardless of the selected design approach, all NEC requirements for motor protection must be satisfied upon transfer to bypass. This includes motor short circuit and overload protection. The bypass should be rated for motor starting current rather than motor full load current; this is necessary so that the motor can be safely started when on bypass.

4.2.4.4. When bypass capability is provided, a disconnect switch for the ASD should also be provided as shown in Figures 4.5 and 4.6. This allows electrical isolation for ASD repair, replacement, or testing.

4.2.4.5. ASD manufacturers are capable of providing bypass capability with an ASD. The procurement specification should list the desired bypass features.

4.2.4.6. Bypass operation should consider the effect of full speed motor operation on the load. In some system designs, it will be acceptable for the motor and driven load to operate at full speed. In other system designs, it might be necessary to restore the previous method of flow control or otherwise limit the flow. For example, an HVAC system might have been controlled by inlet vanes. Upon installation of an ASD, the inlet vanes should have been repositioned to full open. But, on bypass operation, the inlet vanes might need to be repositioned or directly controlled, depending on the situation.

4.2.5. Acoustical Noise. In some installations, an ASD will increase the motor's acoustical noise level. The noise occurs when the ASD's non-sinusoidal current and voltage waveforms produce vibrations in the motor's laminations. The non-sinusoidal current and voltage waveforms are a consequence of the ASD transistor switching (carrier) frequency. Newer ASDs tend to operate at higher carrier frequencies, which reduces the non-sinusoidal output. Some ASDs include special provisions designed specifically to reduce acoustical noise. For locations with low ambient noise level, the acoustical noise generated in a motor by its ASD can be noticeable. The location for an ASD should be evaluated to determine if the procurement specification should address noise as a design consideration. For existing installations with acoustical noise problems, a load reactor might be required to reduce the noise.

4.2.6. Other Design Considerations. Additional design considerations are provided in paragraphs 4.6. though 4.7.2.

4.3. Power Quality:

4.3.1. Introduction:

4.3.1.1. The term *power quality* has different meanings, depending on the user, the application, and the type of electrical system disturbance. All definitions of power quality somehow relate to the relative frequency and magnitude of deviations in the incoming power supplied to electrical equipment from the normal, steady-state, 60 hz sinusoidal waveform of voltage and current. These aberrations can affect the operation of electrical equipment. The term *poor power quality* means that there is sufficient deviation from the normal voltage and current waveform to cause equipment misoperation or premature failure. Conversely, *good power quality* means that there is a low level or incidence of these deviations. Obviously, such general definitions of good and poor power quality depend on the equipment used in the system: some equipment might be very resistant to power aberrations while other equipment might fail quickly under equivalent conditions.

4.3.1.2. Potential power quality concerns associated with ASDs include:

4.3.1.2.1. Harmonic distortion on the line side and the load side of the ASD.

4.3.1.2.2. Nuisance tripping of ASDs because of voltage sags and momentary interruptions.

4.3.1.2.3. Motor overheating because of ASD-generated harmonic currents.

4.3.1.2.4. Motor winding or bearing failure caused by overvoltages due to ASD-generated voltage high rise times.

4.3.1.2.5. Notching and transient oscillations associated with power electronics switching.

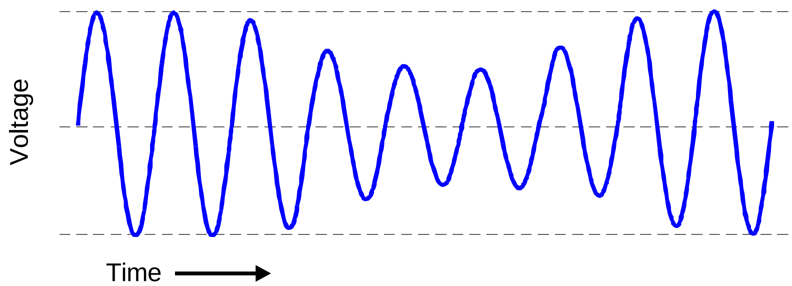
4.3.1.2.6. Nuisance tripping of ASDs caused by capacitor switching transients.

4.3.1.3. Refer to AFMAN(I) 32-1181 for a detailed overview of power quality issues and design solutions. AFMAN(I) 32-1181 provides extensive design criteria related to power quality, including designing the electrical system for nonlinear loads and neutral circuit sizing for nonlinear loads. This chapter supplements AFMAN(I) 32-1181 specifically with regard to ASDs. Power quality issues should be addressed at the design phase to ensure they do not become problems after ASD installation.

4.3.2. Voltage Sags:

4.3.2.1. A voltage sag is a decrease in the supplied voltage, outside of the normal system tolerance, usually with a duration of about one cycle to less than a few seconds. Figure 4.7 shows an example waveform of a voltage sag.

Figure 4.7. Voltage Sag.



4.3.2.2. Voltage sags can be caused by the following conditions:

4.3.2.2.1. Faults on adjacent feeders causing a reduction in nearby voltages.

4.3.2.2.2. Faults in the commercial power system.

4.3.2.2.3. Starting of large loads.

4.3.2.2.4. Overloaded or undersized wiring.

4.3.2.2.5. Utility switching.

4.3.2.2.6. Equipment failure.

4.3.2.3. ASDs should be protected against voltage sags by two levels of protection:

4.3.2.3.1. An ASD should have a minimum of 3-cycle ride-through capability; this ensures that the ASD should not deenergize during most momentary transients. Verify with the manufacturer the specific speed and torque performance during and after a voltage sag.

4.3.2.3.2. Ride-through capability will not keep an ASD operating through longer duration voltage sags or temporary interruptions. For these conditions, the ASD should have a second level of protection—automatic reset circuitry that will automatically restart the ASD upon restoration of adequate quality power.

4.3.3. Overvoltages Caused by Long Motor Leads:

4.3.3.1. Standard motors have been designed to receive sinusoidal power. The fast switching of insulated gate bipolar transistors (IGBTs) inside a PWM ASD causes a voltage surge to be developed on the ASD and motor terminals. The surge has a steep wave front, which causes the motor cable to appear as a transmission line. Each voltage pulse reflects back and forth between the ASD and motor terminals. These reflected pulses add to the inverter output voltage and can cause the motor terminal voltage to be as high as twice the rated voltage. The magnitude of this overvoltage depends on the IGBT rise time and the cable length between the ASD and the motor. Also, the high switching frequency can cause uneven voltage distribution within the motor windings, often causing an overvoltage on the first winding. The net effect of this voltage is stress on the motor insulation and it can lead to early motor failure. Depending on the motor design, the high voltage rise time can also induce bearing currents, leading to premature bearing failure. As an example, one facility reported that over half of its 10 horsepower motors powered by PWM drives failed within 30 days after they were installed. It was assumed that the motors were defective and all of the motors were replaced with new motors of another make. But, within one week, these new motors also began to fail. Investigators found that the cables connecting the drives and motors were about 100 feet (30.5 meters) long and the voltages at the motor terminals were about 1,500 volts peak.

4.3.3.2. Overvoltage effects can be minimized by the following approaches:

4.3.3.2.1. Specify motors that are designed for ASD applications. These are often referred to as *inverter duty* motors and they are designed to withstand the overvoltages generated by an IGBT ASD.

4.3.3.2.2. Minimize the cable length between the ASD and the motor. Verify with the ASD manufacturer the maximum recommended distance for acceptable long term operation.

4.3.3.3. Both of the above are recommended whenever a new motor is procured as part of the ASD installation. If ASD-duty (commonly referred to as *inverter duty*) motors are not used or if cable lengths are longer than 20 feet (6 meters) between the ASD and the motor for standard design motors, additional design measures might be required. One of the following approaches can reduce the overvoltage at the motor terminals:

4.3.3.3.1. Install a motor terminal filter. This type of filter connects in shunt at the motor terminals and matches the motor and cable surge impedances. The design depends on the cable length.

4.3.3.3.2. Install an ASD output filter. This type of filter connects in series to the ASD output and reduces the rate of voltage rise to an acceptable level. The design depends on the cable length. An ASD output filter would be used instead of a motor terminal filter if the motor terminals are inaccessible, such as with a submersible pump.

4.3.3.3.3. Install a load reactor. Paragraphs 4.3.5.4 through 4.3.5.5 describe the application of load reactors. If a load reactor is not required for other reasons, a motor terminal filter or ASD output filter is a simpler alternative.

4.3.4. Overvoltages Caused by Nearby Capacitor Switching:

4.3.4.1. Each time a power system capacitor is energized, a transient voltage oscillation occurs between the capacitor and the power system inductance. The transient overvoltage can be twice the normal system voltage at the capacitor location. Furthermore, these transient overvoltages can be magnified within the facility if low-voltage capacitor banks have been installed for power factor correction.

4.3.4.2. Smaller ASDs usually have a VSI rectifier and use a PWM inverter to supply the motor. The dc link between the rectifier and the inverter often has a fairly narrow range of allowed operation and it is not uncommon for an ASD to trip whenever the dc overvoltage exceeds 120 percent or less of the rated value. Capacitor switching transients can cause a current surge into the dc link capacitor, causing an overvoltage and subsequent ASD trip. Nuisance tripping of this type can occur several times a day as the utility switches nearby substation capacitors.

4.3.4.3. Filter reactors can be necessary to correct nuisance ASD tripping of this type. A series inductance on the input of the ASD reduces the current surge into the ASD, thereby reducing the dc link overvoltage. Refer to paragraphs 4.3.5 through 4.3.5.5 for additional information regarding filter reactors.

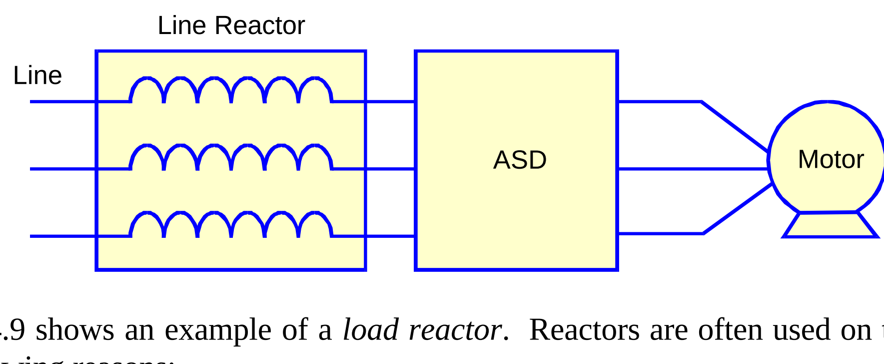
4.3.5. ASD Filter Reactors for Harmonic Distortion Mitigation:

4.3.5.1. ASDs generate harmonic distortion and are also sensitive to harmonic distortion. IEEE 519, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, provides the industry-accepted method of evaluating harmonic voltages and currents. IEEE 519 provides *system level* guidance, not equipment specific guidance. What this means is that harmonic distortion limits are established for the facility and the installation of any equipment should not degrade the system to beyond acceptable levels. Meeting IEEE 519 limits can be easy for a facility with primarily linear loads, and it can be very difficult and costly for a facility with predominantly nonlinear loads. As an example, some facilities have installed many ASDs for HVAC system motors in an attempt to reduce energy usage. Unfortunately, each ASD generates current harmonic distortion and nuisance tripping of other equipment has occurred at some facilities as a consequence. Refer to AFMAN(I) 32-1181 for a detailed discussion of harmonic distortion and its effects.

4.3.5.2. To limit the impact of harmonic distortion, filtering is recommended on the line side of the ASD. Reactors can be a cost-effective solution for control of harmonic distortion. Reactors provide a filtering function by blocking offending harmonic currents, thereby lessening the harmonic effects elsewhere in the facility.

4.3.5.3. Figure 4.8 shows a *line reactor*, a reactor applied on the line side of a device. Line reactors are used on the line side of an ASD to minimize harmonic distortion and reduce the magnitude of voltage spikes in the electrical system. A line reactor serves the dual purpose of improving the power quality supplied to the ASD while also minimizing the effect of the ASD on the rest of the electrical system; ASDs do contribute to the electrical system's total harmonic distortion.

Figure 4.8. Line Reactor.



4.3.5.4. Figure 4.9 shows an example of a *load reactor*. Reactors are often used on the load side of an ASD for the following reasons:

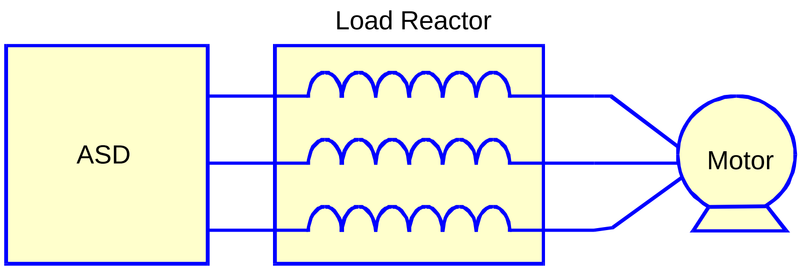
4.3.5.4.1. To provide protection under motor short circuit conditions by acting as a current limiting device. The reactor slows the rate of rise of the short circuit current and limits the short circuit current to a more manageable level. By slowing the rate of current rise, the reactor allows more time for the ASD's protective circuit to react to the fault.

4.3.5.4.2. To absorb motor-generated surges that might otherwise cause the ASD to trip.

4.3.5.4.3. To reduce harmonic distortion to the motor, which can improve motor efficiency and life.

4.3.5.4.4. To reduce the voltage rise time of the ASD output.

Figure 4.9. Load Reactor.



4.3.5.5. Reactors are rated in terms of percent impedance. Higher impedance reactors provide greater filtering, but also increase the voltage drop. For example, a 3 percent impedance reactor will introduce a 3 percent voltage drop across it under rated conditions. Evaluate the effect of the additional voltage drop as part of any filter application.

4.3.6. Isolation Transformers. Isolation transformers can be used on the input of an ASD to reduce the harmonic distortion effect of the electrical system upstream of the ASD. If the only purpose of the isolation transformer is to reduce the level of harmonic distortion, a line reactor will be a more cost-effective approach.

4.4. Energy Efficiency Analysis:

4.4.1. ASDs can provide a substantial energy savings when applied to lightly loaded motors. Fully loaded motors will show little or no energy savings.

4.4.2. ASDs often show a rapid payback when installed on variable air volume (VAV) fan motors to control fan speed. By controlling the fan motor's speed and torque, the system can efficiently adjust fan speed as necessary to satisfy building load conditions. Rather than running at full speed 90 percent to 95 percent of the time, a fan motor controlled by an ASD can operate at speeds of 80 percent or less which can reduce energy consumption by up to 50 percent, or more. The potential energy savings are calculated by the affinity laws for fans as follows (Figure 4.10 illustrates the variations as a function of speed):

4.4.2.1. Quantity of air flow (cfm) varies directly with the fan speed (rpm):

$$\frac{cfm_2}{cfm_1} = \frac{rpm_2}{rpm_1}$$

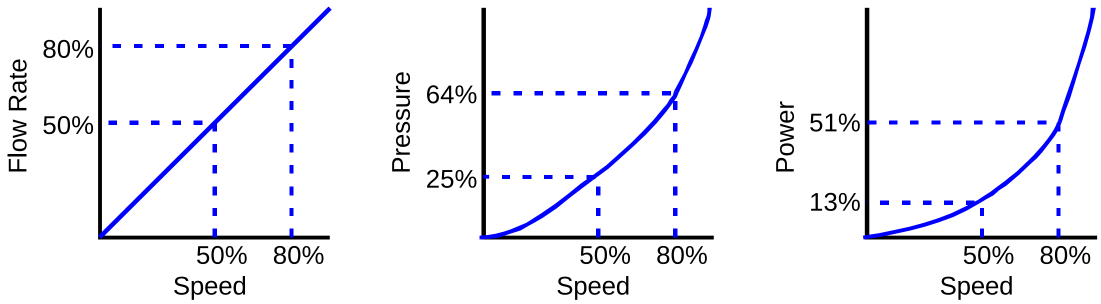
4.4.2.2. Pressure (p) varies with the square of the fan speed:

$$\frac{p_2}{p_1} = \left(\frac{rpm_2}{rpm_1}\right)^2$$

4.4.2.3. Brake horsepower (hp) varies with the cube of fan speed:

$$\frac{hp_2}{hp_1} = \left(\frac{rpm_2}{rpm_1}\right)^3$$

Figure 4.10. Illustration of Affinity Laws.



$$\frac{cfm_2}{cfm_1} = \frac{rpm_2}{rpm_1} \qquad \frac{p_2}{p_1} = \left(\frac{rpm_2}{rpm_1}\right)^2 \qquad \frac{hp_2}{hp_1} = \left(\frac{rpm_2}{rpm_1}\right)^3$$

4.4.3. ASDs can also be used to reduce the energy consumption of centrifugal chillers. ASDs are often installed on only one chiller per system because the fixed speed chillers can be staged for base load, with the ASD-controlled chiller varying capacity according to swings in the load. Savings can be significant provided the following conditions are met:

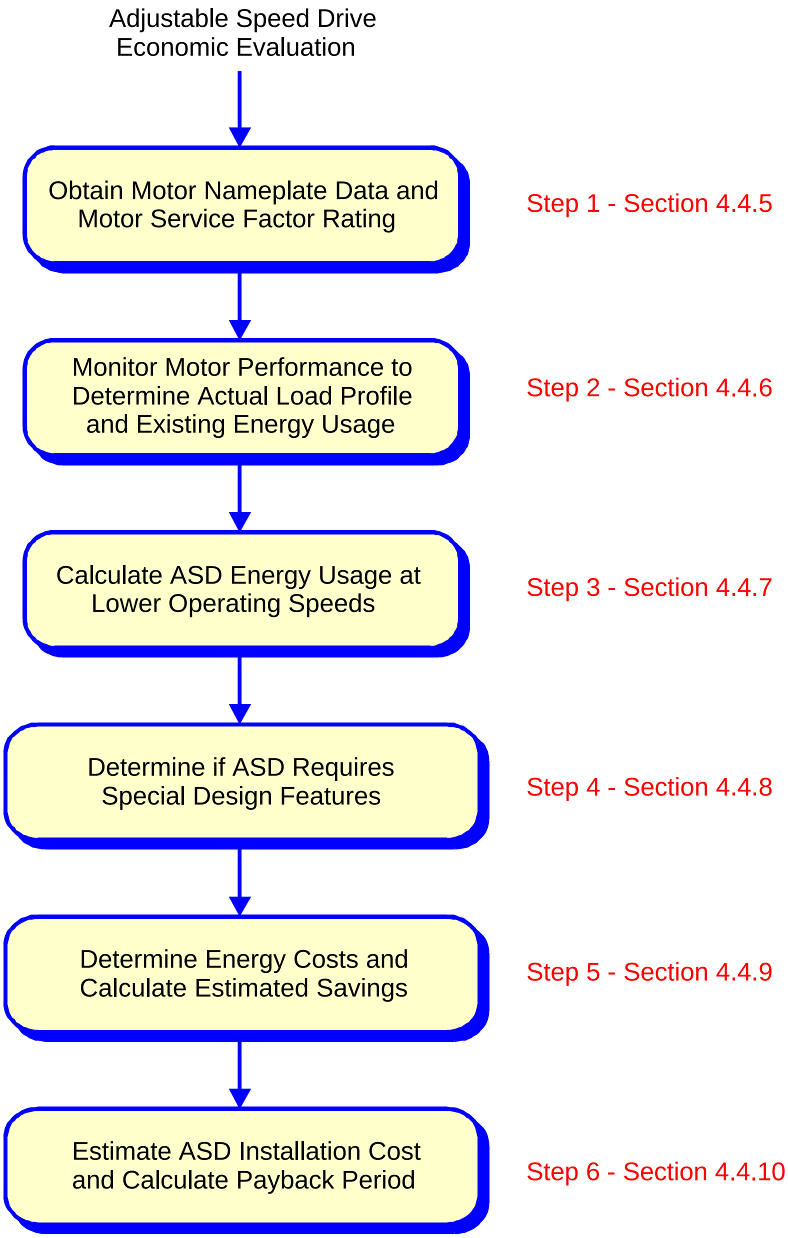
4.4.3.1. Loads are light for many hours per year.

4.4.3.2. The climate does not have a constant high wet bulb temperature.

4.4.3.3. The condenser water temperature can be reset higher under low part load conditions.

4.4.4. If an ASD installation is considered on the basis of energy efficiency, perform an economic evaluation in accordance with the process shown in Figure 4.11.

Figure 4.11. ASD Economic Evaluation.



4.4.5. Obtain Motor Nameplate Data—Step 1 of Figure 4.11:

4.4.5.1. The motor nameplate data is needed to verify that the motor is capable of acceptable operation with an ASD. Older motors might overheat at lower operating speeds and also might require special protection against ASD overvoltages.

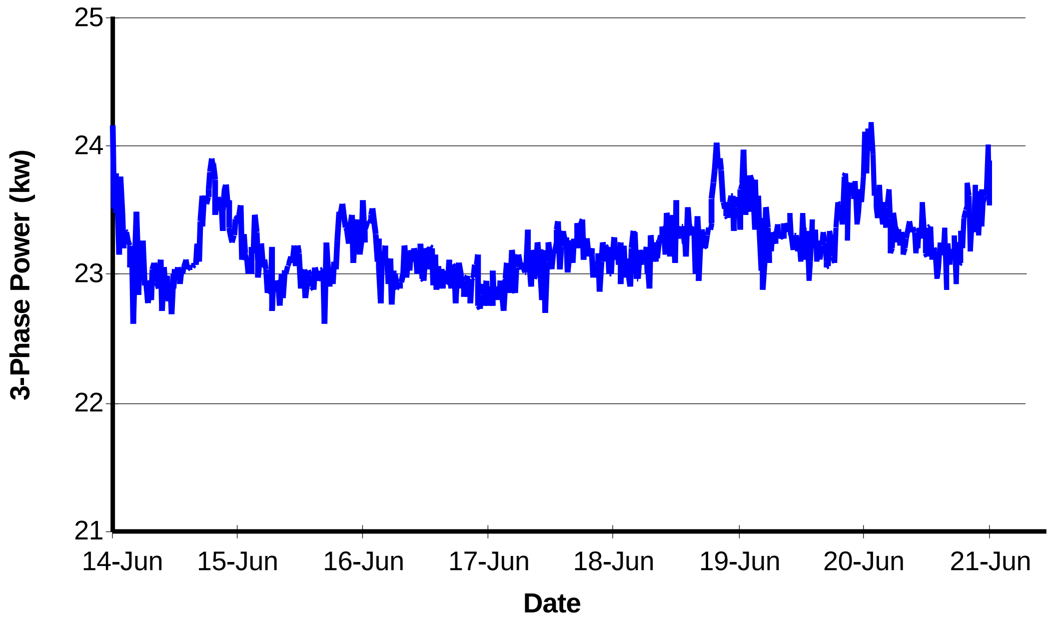
4.4.5.2. Confirm with the motor manufacturer the limits associated with operating an existing motor by an ASD. Determine if motor replacement is needed as part of the ASD design.

4.4.5.3. Refer to paragraphs 4.2.2 through 4.2.2.4 for additional information regarding motor design criteria for an ASD application.

4.4.6. Determine Actual Motor Load—Step 2 of Figure 4.11:

4.4.6.1. The key to an economic evaluation is to determine whether or not the motor will be fully loaded under expected operating conditions. If the motor is always loaded at or near 100 percent of rated load, then little if any savings will be realized by the installation of an ASD. However, it is common to discover that the actual load current is significantly less than rated. For example, Figure 4.12 shows an example in which a 60 horsepower (44.8 kW) motor used in an HVAC application normally operates at a load of less than 24 kW. In this case, an ASD can provide substantial savings.

Figure 4.12. Example Motor Load Profile With Motor Operating at Half of Rated Load.



4.4.6.2. Estimate the operating time for each evaluated motor. As an example, Figure 4.12 shows that the evaluated motor operated continuously during the monitored period.

4.4.6.3. Calculate the full load input power (kW) of the motor by multiplying its nameplate horsepower by 0.746 and by dividing by the motor's full load efficiency:

$$Motor\ Full\ Load\ Input\ Power\ (kW) = \frac{Rated\ hp \times \dfrac{0.746\ kW}{hp}}{Full\ Load\ Efficiency}$$

4.4.6.4. Estimate the load profile for each evaluated motor. Figure 4.12 shows an example in which the motor operated near 50 percent of rated load, with little variation in load. In many cases, the one-week load profile shown in Figure 4.12 will be repeated each week. In other cases, the load cycle might have seasonal variations. Some applications will exhibit greater load variation even on a daily cycle; for example, a simple load profile for a motor might be estimated as follows:

4.4.6.4.1. 50 percent of operating time—60 percent of rated load.

4.4.6.4.2. 25 percent of operating time—70 percent of rated load.

4.4.6.4.3. 25 percent of operating time—80 percent of rated load.

4.4.6.5. The energy use can be estimated for a given horsepower motor by the following expression:

$$Energy\ Use\ (kWh) = \frac{Rated\ \ Horsepower \times \frac{0.746\ kW}{hp}}{Rated\ \ Efficiency} \times (\#\ of\ \ hours\ \ annual\ \ use) \times (load\ \ factor)$$

EXAMPLE: A 50 horsepower motor with rated efficiency of 94 percent, operating continuously throughout the year (8,760 hours) at a load factor of 75 percent, has the following expected energy use:

$$Energy\ Use\ (kWh) = \frac{50\ hp \times \frac{0.746\ kW}{hp}}{0.94} \times (8{,}760) \times (0.75) = 260{,}703\ kWh\ \ per\ \ year$$

4.4.6.6. The above information is needed to characterize the existing energy usage and to predict energy usage with an ASD.

4.4.7. Calculate Predicted ASD Energy Usage—Step 3 of Figure 4.11:

4.4.7.1. The goal is to obtain an energy savings by operating the motor at a lower speed while still satisfying the load requirements. The ideal application is one defined by the affinity laws of Figure 4.10 in which power varies with the cube of the motor speed:

$$\frac{hp_2}{hp_1} = \left(\frac{rpm_2}{rpm_1}\right)^3$$

4.4.7.2. The expected energy usage with an ASD varies with the following parameters:

4.4.7.2.1. Load profile or energy use.

4.4.7.2.2. Percent time that ASD can operate motor at reduced speed.

4.4.7.2.3. Predicted motor speed with ASD operation.

4.4.7.2.4. ASD Efficiency.

4.4.7.3. Applying the affinity laws, use the following equation to predict the energy use with an ASD:

$$ASD\ \ Energy\ Use\ (kWh) = \frac{Full\ \ Load\ \ (kW)}{ASD\ Rated\ \ Efficiency} \times (Percent\ \ Rated\ \ Speed)^3 \times (Number\ \ of\ \ Hours)$$

EXAMPLE: Assume the rated full load is 40 kW, the ASD rated efficiency is 95 percent, the load requirements can be satisfied at a constant reduced speed of 70 percent of rated speed, and the motor will run continuously throughout the year (8,760 hours). The expected energy use with an ASD is given by:

$$ASD\ Energy\ Use\ (kWh) = \frac{40\ kW}{0.95} \times (0.7)^3 \times (8{,}760\ hours) = 126{,}513\ kWh$$

4.4.8. Determine if ASD Requires Special Design Features—Step 4 of Figure 4.11:

4.4.8.1. ASDs are often provided with a minimum of features; the user is expected to specify the options and design features that are necessary for the given application. ASD manufacturers often ensure competitive pricing by including design options only as specified by the user.

4.4.8.2. An ASD economic evaluation should be based on the expected ASD installation price including necessary design options. For example, in some cases, it will be necessary to install a new motor, include a complete ASD bypass design, and install special power quality design features. Each of these additions might well be necessary to ensure a reliable design, but they will also increase the ASD installation cost, thereby extending the payback time.

4.4.8.3. Ensure that the economic evaluation is based on a satisfactory ASD design and reflects the expected procurement and installation cost of a better quality installation.

4.4.9. Determine Energy Costs and Calculate Estimated Savings—Step 5 of Figure 4.11. The average energy cost per kWh, including demand charges, should be used to determine the expected annual energy savings. The energy costs should be based on actual local utility charges.

EXAMPLE: If the existing motor installation uses 100,000 kWh annually, operation with an ASD is expected to use only 36,000 kWh annually, and the average energy cost is \$0.06/kWh, the estimated annual energy savings is given by:

$$ASD\ Annual\ Energy\ Savings = (100{,}000\ kWh - 36{,}000\ kWh) \times \$0.06 / kWh = \$3{,}834$$

4.4.10. Estimate ASD Installation Costs and Calculate Payback Period—Step 6 of Figure 4.11:

4.4.10.1. Paragraphs 4.4.8 through 4.4.8.3 describe the process of determining the ASD design requirements and the associated cost of special design features. This information is needed to determine the expected total installation cost of the ASD and associated equipment.

EXAMPLE: The previous example calculated a predicted annual savings of \$3,834 per year. Assume the expected ASD installation cost is \$10,000. The payback time is calculated as follows:

$$Payback\ Time\ (years) = \frac{ASD\ Installation\ Cost}{Annual\ Energy\ Savings} = \frac{\$10{,}000}{\$3{,}834} = 2.6\ years$$

EXAMPLE: Table 4.1 provides a sample economic evaluation for an ASD installation for a continuously operating HVAC system motor. This evaluation was for an application in which higher initial ASD costs were expected to address harmonic distortion concerns as part of the design. Even so, a payback period of about two years is estimated.

Table 4.1. Example ASD Energy Savings Worksheet.

Input Data for Existing Application				
Motor ID #	HVAC Fan - 1	Comments		
Motor Horsepower	60	Larger motors provide greater payback.		
Motor Efficiency (From Nameplate)	91.7%	Evaluate efficiency at less than full load.		
Motor Load Factor	50.0%	Existing energy usage is lower if the motor is operating at less than full load. This value is obtained from metering or monitoring.		
Number Hours Operation per Year	8,760	Hours of operation per year is particularly important to energy analysis.		
Existing Motor Energy Use (kWh/yr)	213,794	$= [(60 \times 0.746)/0.917] \times 8760 \times 0.5$		
Calculation for Adjustable Speed Operation				
ASD Efficiency	95.0%			
Operating Schedule With ASD	Frequency	Percent Speed	Percent Time	Energy (kWh)
$32{,}812 = [213{,}794 \times (0.9)^3 \times 0.2]/.95$	54	90.0%	20.0%	32,812
$40{,}328 = [213{,}794 \times (0.8)^3 \times 0.35]/.95$	48	80.0%	35.0%	40,328
$27{,}017 = [213{,}794 \times (0.7)^3 \times 0.35]/.95$	42	70.0%	35.0%	27,017
$4{,}861 = [213{,}794 \times (0.6)^3 \times 0.1]/.95$	36	60.0%	10.0%	4,861
Estimated Energy Use With ASD			Total:	105,018
Economic Analysis and Payback Calculation				
Annual Energy Savings (kWh):	108,776	= (213,794 - 105,018)		
Cost per Kilowatt Hour:	$0.06	Based on local commercial power rates.		
Annual Cost Savings:	$6,527	$= (108{,}776 \times \$0.06)$		
Estimated Installation Cost Per Motor Horsepower:	$225	Estimate based on ASD operating requirements and features.		
Estimated Installation Cost:	$13,500	$= (60 \text{ hp} \times \$225)$		
Payback Period (Years)	2.07	= (13,500/6,527)		

4.4.10.2. As can be seen in Table 4.1, an ASD economic evaluation is most sensitive to the following assumptions:

4.4.10.2.1. Total Motor Operating Time Per Year. Unless it is fully loaded, a continuously energized motor will show a faster payback than an intermittently energized motor.

4.4.10.2.2. Estimated Actual Motor Load/Speed. For a standard centrifugal fan motor, energy usage is proportional to the cube of the speed. For example, if the motor speed can be reduced to 80 percent of rated speed, the energy usage can be reduced to almost 50 percent of its nominal value.

4.4.10.2.3. Cost Per Kilowatt Hour. The local average energy cost should be used.

4.4.10.2.4. ASD Equipment and Installation Cost. For critical locations, the added cost of ensuring acceptable power quality can double the total initial cost. Even so, an acceptable payback is frequently obtained.

4.4.10.3. Payback periods greater than 5 years should not be approved solely on the basis of economic savings; operating system improvements should also be an identified need for these cases.

4.4.10.4. Table 4.1 uses a constant ASD efficiency of 95 percent for this simple example. The ASD manufacturer can provide the actual ASD efficiency as a function of speed. A single average efficiency is often acceptable down to 50 percent speed. Below this speed, ASD efficiency declines rapidly and actual efficiency values should be used as provided by the manufacturer.

4.4.10.5. The motor load factor or load profile is an important value to establish as part of the analysis. Motors are rarely fully loaded and assuming full load operation will inappropriately inflate the expected savings. Power or current measurements for at least a week should be recorded to ensure the load is properly characterized. If seasonal variations are expected, this should also be factored into the analysis.

4.4.10.6. Although ASD energy savings calculations can be performed manually on a spreadsheet as shown in Table 4.1, ASDMaster® is recommended as the preferred method of performing ASD energy efficiency analyses. ASDMaster® will provide a detailed analysis of the system to establish the expected savings. Table 4.1 is provided to illustrate an energy savings analysis and the example was deliberately kept simple by applying the affinity laws. Refer to paragraphs 4.5.2 through 4.5.2.3 for information regarding the ASDMaster® energy efficiency analysis.

4.5. ASDMaster® Evaluations:

4.5.1. Introduction:

4.5.1.1. ASDMaster® is a software program developed by the Electric Power Research Institute for the evaluation of ASDs. It consists of six different modules as follows:

4.5.1.1.1. Instruction. Provides basic information regarding ASD operation, analytical methods, power quality, and its impact on ASD equipment.

4.5.1.1.2. Energy Analysis. Computes energy usage of conventionally controlled equipment. Provides examples for various application types.

4.5.1.1.3. Other Benefits. Assists in the evaluation of non-energy-savings benefits as part of an economic assessment.

4.5.1.1.4. Equipment Specification. Generates an equipment specification and serves as a checklist for the consideration of various ASD options and features.

4.5.1.1.5. Database. Includes a database of standard ASDs with search capability to reduce the list to those ASDs appropriate for the application.

4.5.1.1.6. Economic Analysis. Calculates the economic benefit of installing an ASD. A complete economic report can be prepared.

4.5.1.2. ASDMaster® is recommended for the evaluation of ASD applications. ASDMaster® is available from the Bonneville Power Administration, Energy Efficiency, PO Box 3621-NCP, Portland, Oregon, 97208-3621, and it can be ordered by telephone at 1-800-973-7479.

4.5.2. ASDMaster® Energy Efficiency Analysis:

4.5.2.1. ASDMaster® should be used as a screening tool to determine if an ASD application will provide an adequate level of energy savings. ASDMaster® has a built-in screening algorithm to determine if the expected energy savings will be adequate. This screening algorithm provides a quick and easy method to screen out applications that are not good candidates for adequate energy savings. The screening algorithm is based on the following inputs:

4.5.2.1.1. Type of load. If the torque and horsepower requirements of the load decrease with decreasing speed, the application is likely to be a good candidate for an ASD retrofit.

4.5.2.1.2. Load duty cycle. If the load is often well below 100 percent of rated load, the savings can be substantial.

4.5.2.1.3. Motor size. ASDs cost more with increasing horsepower requirements, but the potential energy savings increase even more. Larger motors are likely to be better candidates for energy savings.

4.5.2.1.4. Total operating hours. The maximum operating time per year is 8,760 hours. Applications that run more than 6,000 hours per year are usually good candidates and applications that run less than 2,500 hours per year are often poor candidates.

4.5.2.2. ASDMaster® keeps the initial analysis simple by declaring the application as good, probably marginal, or probably not a good application. This simplified approach allows the designer to quickly focus on the most cost-effective applications for ASDs.

4.6. ASD Equipment Specifications:

4.6.1. Introduction:

4.6.1.1. Consider three aspects of an ASD application as part of a specification:

4.6.1.1.1. The environment for the new ASD equipment.

4.6.1.1.2. The motor to be controlled.

4.6.1.1.3. The ASD to be used.

4.6.1.2. A basic need in the specification of the ASD is to define the ASD application as concisely as possible. Limit information to that which is relevant to the application of the ASD within the overall system. The best specification is one that does not over specify or over simplify. Avoid specifying items that are desirable but not necessary, items that can not be directly assessed or measured, and items that are internal ASD manufacturing design decisions. Specify to ensure the "fitness of purpose" of those aspects of the ASD that can be directly evaluated.

4.6.1.3. ASDMaster® can be used for the generation of ASD-related equipment specifications. ASDMaster® effectively functions as an equipment specification checklist to ensure important ASD features are considered. Upon completion of the equipment specification module, ASDMaster® generates a complete equipment specification in a format readily understandable by equipment manufacturers.

4.6.1.4. Attachment 4 provides an example equipment specification; the purpose of this attachment is to illustrate the type of information needed for a specification.

4.6.2. Motor Information:

4.6.2.1. Either an existing motor might be retrofitted with an ASD or a new motor might be installed with the ASD. In either case, the motor nameplate information must be provided to the ASD vendor. Information of interest includes:

4.6.2.1.1. Motor type and NEMA classification.

4.6.2.1.2. Enclosure type.

4.6.2.1.3. Horsepower rating.

4.6.2.1.4. Current, frequency, and voltage rating.

4.6.2.1.5. Rated speed and maximum allowable speed.

4.6.2.1.6. Rated efficiency.

4.6.2.1.7. Service factor.

4.6.2.1.8. Bearing type.

4.6.2.2. For an existing motor, it is important to establish that it is sized to provide the necessary load torque while operating at reduced speed. The motor's power capability can be restricted at low speed because the motor's shaft-mounted cooling fan is less effective at low speed. Compare the motor output capability with the load requirement over the full speed range. A constant-speed motor-driven fan might be required to cool the motor in such applications as constant torque loads. Also, with an existing motor, ensure that the bearing system will operate properly over the entire speed range. Antifriction bearings are usually acceptable at all speeds; however, sleeve bearings have a minimum continuous operating speed to ensure lubrication.

4.6.2.3. ASDs usually generate a steep-fronted output waveform that has a higher voltage rate of change than a standard 60 hz waveform. This high rate of voltage change can exceed the voltage rating of existing induction motor windings. The ASD vendor should be informed of the type and age of the motor to ensure that it will perform properly in an ASD environment. The ASD vendor might recommend cable termination devices designed to attenuate transient voltages and might require cable lengths of less than 50 feet (15 meters) between the ASD and the motor.

4.6.2.4. Antifriction bearings can be affected by the PWM voltage waveforms applied to the motor stator. Capacitive coupling from the stator winding to the rotor can create elevated static voltages. Unless a safety path is provided for the static charge, the voltage level can build up to a level that will cause electrical discharge through the lubricant of the antifriction bearing. Each electrical discharge can produce a small pit on the bearing and repeated discharges will shorten the bearing life. A safety discharge path can be provided by a ground brush on the motor, electrically conductive grease, or other methods provided by the ASD or motor vendor.

4.6.2.5. Motor nameplate information is important in the selection of the correct ASD and associated equipment. Motor speed is particularly important because ASDs are rated according to number of poles. Applications above 6 poles might require ASD derating to accommodate higher reactive currents.

4.6.2.6. For new motors, the motor vendor should be informed that the application is associated with an ASD. New motors should be purchased as inverter duty motors.

4.6.3. Motor Interface:

4.6.3.1. The cable length between the ASD and the motor is an important specification item. Depending on the cable length, the ASD vendor might recommend additional voltage protection for the motor.

4.6.3.2. The ASD might provide some level of protection for the motor. The ASD vendor needs to understand the protection requirements so that thermal protection is designed properly.

4.6.4. Power Supply:

4.6.4.1. The ASD has to interface with the existing electric supply. The following electrical system features and characteristics should be known:

4.6.4.1.1. Short circuit current available from the electric supply.

4.6.4.1.2. Harmonic content of the supply voltage before the ASD is applied.

4.6.4.1.3. Degree of voltage unbalance in the supply to the ASD. Voltage unbalance can cause additional heating in both motors and ASDs.

4.6.4.1.4. Magnitude and time duration of sags and swells in the supply voltage.

4.6.4.1.5. Variations in electrical supply frequency.

4.6.4.1.6. Presence of automatic power factor correction capacitors, which can cause ASD tripping due to switching transients.

4.6.4.1.7. Surge transient frequency.

4.6.4.2. If a standby or emergency source of power is available, the above information should be provided for this power source also. For example, commercial power experiences very minor frequency variations, but an onsite engine generator might have significant frequency variations.

4.6.5. Enclosure and Enclosure Options:

4.6.5.1. The selected enclosure type depends on the environment around the ASD. Inspect the area where the ASD is intended to be installed and evaluate for the following types of environmental concerns:

4.6.5.1.1. Large quantities of airborne material, conductive, abrasive, or explosive dust. This material can collect on unprotected ASD equipment, causing overheating or electrical faults.

4.6.5.1.2. Humid and chemically-laden atmospheres that can penetrate the surface of electrical components, thereby shortening the life of electrical equipment.

4.6.5.1.3. Presence of rodents, insects, ants, birds, or snakes. The warmth of an ASD cabinet will attract these pests and the enclosure should be designed to keep them out.

4.6.5.1.4. Ambient temperatures above 104 °F (40 °C). Keeping the ASD equipment clean and cool will provide the best conditions for reliable operation.

4.6.5.1.5. Complying with equipment clearances and guarding requirements.

4.6.5.2. Enclosure selection also includes the following items:

4.6.5.2.1. Instruments and controls.

4.6.5.2.2. Safety interlocks and lighting.

4.6.5.2.3. Paint type and color.

4.6.5.2.4. Heat rejection capability.

4.6.6. System Environment:

4.6.6.1. ASDs are usually designed to operate in a maximum ambient temperature range of 104 °F (40 °C) to 122 °C (50 °C). But, life will be extended by keeping the ambient temperature around the electronics well below this upper limit. Particular attention is required if the equipment is exposed to direct sunlight. Minimum temperature can be controlled by thermostatically operated space heaters.

4.6.6.2. Specify the humidity at which the ASD will operate. The standard for low voltage ASDs is 95 percent humidity, noncondensing. More severe environments will require special design features.

4.6.6.3. ASDs are designed to reject heat to the surrounding air. Standard designs can operate up to an elevation of 3,000 feet (914 meters) above sea level. Unless supplemental cooling (air conditioning) is provided for altitudes above 3,000 feet (914 meters), the ASD and associated equipment might require derating.

4.6.6.4. ASDs can produce noise from the internal power circuits and associated electronic control circuits. Acceptable noise levels depend on the application environment.

4.6.6.5. Specify for the expected site vibration levels, which should have been previously specified for other installed electrical equipment. Standard low voltage ASDs are often able to withstand 0.2 g (acceleration of gravity) peak at 10 hz to 60 hz.

4.6.7. Efficiency:

4.6.7.1. The desired ASD efficiency should be specified. Efficiencies of 90 percent to 95 percent are achievable at rated output.

4.6.7.2. The efficiency of the ASD and motor should be provided by the vendor as a function of speed. This will allow the designer to estimate more closely the expected energy savings for a given application.

4.6.8. Reliability:

4.6.8.1. The ASD reliability should be addressed at two levels: the inherent reliability and maintainability of the ASD and associated equipment, and the reliability of the ASD when exposed to abnormal conditions.

4.6.8.2. ASD reliability is specified as either the mean time between failure (MTBF) or as a percentage of the ASD population that can fail over a period of time (usually per year). Industry data for MTBFs range from 40,000 to 80,000 hours for good quality ASDs. MTBF data will usually be provided by the manufacturer.

4.6.8.3. The ASD should also be evaluated with respect to the mean time to repair (MTTR) based on knowledge regarding available spare parts. The MTTR will be affected by the ASD mechanical construction and the ease of replacing internal components. Diagnostic tools should help identify the cause of failure.

4.6.8.4. Some reliability features must be specified for the ASD. Bypass capability, redundancy, momentary ride-through, and transient susceptibility can require additional design features.

4.6.9. System Protection:

4.6.9.1. Most ASDs offer a full range of protection features that can be applied to most applications. Review the manufacturer's standard ASD protection features and adopt the desired features in the specification.

4.6.9.2. The most important part of system protection is to evaluate ASD performance under system fault or abnormal conditions. Faults include mechanical overload, electrical short circuit or ground fault in the motor circuit, or an electrical fault upstream of the ASD.

4.6.10. Control Signals:

4.6.10.1. Determine the available signals for control of the ASD and ensure the specification properly describes the signal requirements. The ASD must be compatible with the existing electric controls.

4.6.10.2. ASD output signals are used to provide information regarding the operating condition of the ASD and its load. The required output signals will vary with the facility design.

4.6.10.3. The ASD should have adjustment capability to ensure optimal performance with its motor. The following adjustments should be provided if needed: current limit, voltage boost, overspeed trip, volts per hertz, speed regulation, carrier frequency, skip frequency. The commissioning process will adjust these parameters to obtain the desired performance.

4.6.11. Bypass Capability. A bypass circuit is recommended to allow the motor to be connected directly to the electric supply, completely bypassing the ASD. This ensures that ASD failure can be accommodated without complete system loss. Paragraphs 4.2.4 through 4.2.4.6 describe bypass options.

4.7. Summary of ASD Design Considerations:

4.7.1. ASDs are recommended for facility energy efficiency improvements. However, the ASD design should be carefully evaluated and specified to ensure that ASDs do not cause other electrical system or operational problems. The following summarizes the important design considerations:

4.7.1.1. The ASD, motor, and driven load must be compatible. The motor should be capable of reliable operation with an ASD. Refer to paragraphs 4.2.2 through 4.2.2.4.

4.7.1.2. The ASD should not degrade the electrical system beyond acceptable limits by the generation of harmonic distortion. The ASD should also be capable of withstanding common electrical system transients such as voltage sags. Refer to paragraphs 4.3.2 through 4.3.4.3.

4.7.1.3. Important applications should include the ability to bypass the ASD. Refer to paragraphs 4.2.4 through 4.2.4.6.

4.7.1.4. The ASD should be carefully specified to ensure that it is compatible with the motor, the driven load, and the input control signal. Equipment suppliers should certify full compliance with the specification or identify exceptions. Refer to paragraphs 4.6 through 4.6.11 for additional guidance regarding ASD specifications.

4.7.2. The expected savings and payback to be realized by an ASD installation should be evaluated as discussed in paragraphs 4.4 through 4.4.10.6. Applications with a payback of less than 5 years are preferred and paybacks of less than 2 years are common. The expected savings should not be overly optimistic. After installation, the ASD should be monitored to confirm that the predicted energy savings have been achieved. Refer to paragraphs 4.5.2.2 through 4.5.2.3 for an overview of the applications that are best suited for energy savings by an ASD installation.

Chapter 5

ELECTRICAL PROTECTION

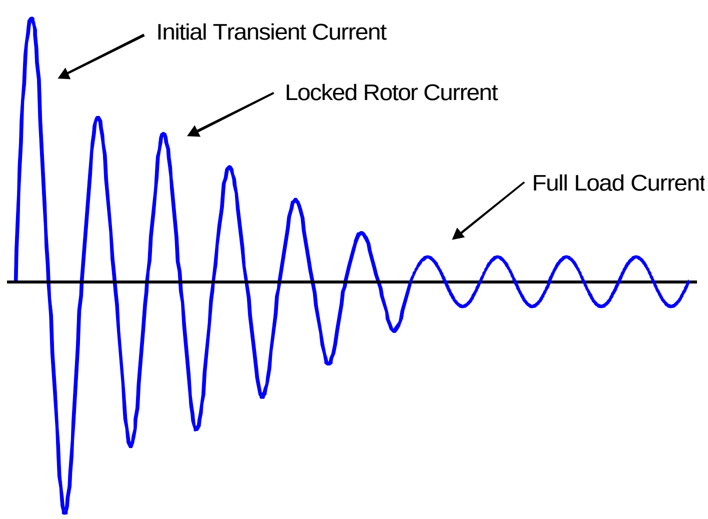
5.1. Motor Starting Currents and Short Circuit Protection:

5.1.1. There are two terms (often misused) pertaining to starting current—momentary inrush current and locked rotor current. The familiar locked rotor current begins after contact closure and tapers off over several seconds while the motor accelerates. Locked rotor current is limited by NEMA standards to roughly six times full load current for both standard and energy efficient Design B motors. Design E motor standards are consistent with European standards and allow a higher locked rotor current in most horsepower ranges, roughly 10 times full load current.

5.1.2. Another aspect of starting current is the momentary inrush current that persists for less than a hundredth of a second, which can substantially exceed locked rotor current. Inrush current can spike as high as 13 times full load current in standard motors and as high as 20 times full load current in Design E and energy efficient Design B motors. Inrush current is too brief to trip thermal protection devices, but energy efficient motors powered through magnetic circuit protectors or other instantaneous trip devices can sometimes experience nuisance starting trips.

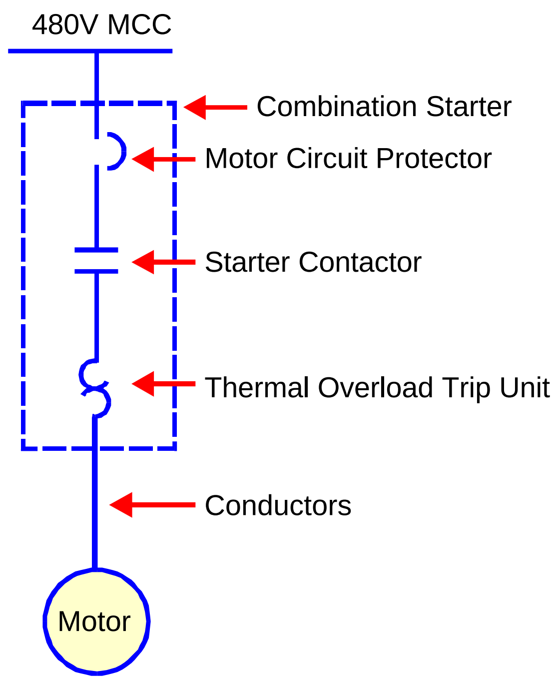
5.1.3. The 1999 National Electrical Code (NEC), Article 430-52, states that the instantaneous setting for an instantaneous only breaker can not exceed 13 times the motor's full load current, and 17 times for Design E or Design B energy efficient motors (this NEC article continues to change with each revision and should be reviewed whenever high starting currents are expected). Unfortunately, this limit may not always be adequate to prevent nuisance breaker trips during some motor starting transients. When the circuit is closed to provide power to a motor, the initial current consists of two components: a sinusoidal steady-state current and a transient component current that rapidly decays away. After a few milliseconds, only the sinusoidal term remains with a magnitude corresponding to the motor locked rotor current. As the motor accelerates, the current eventually falls to the normal full load value (see Figure 5.1).

Figure 5.1. Motor Starting Current.



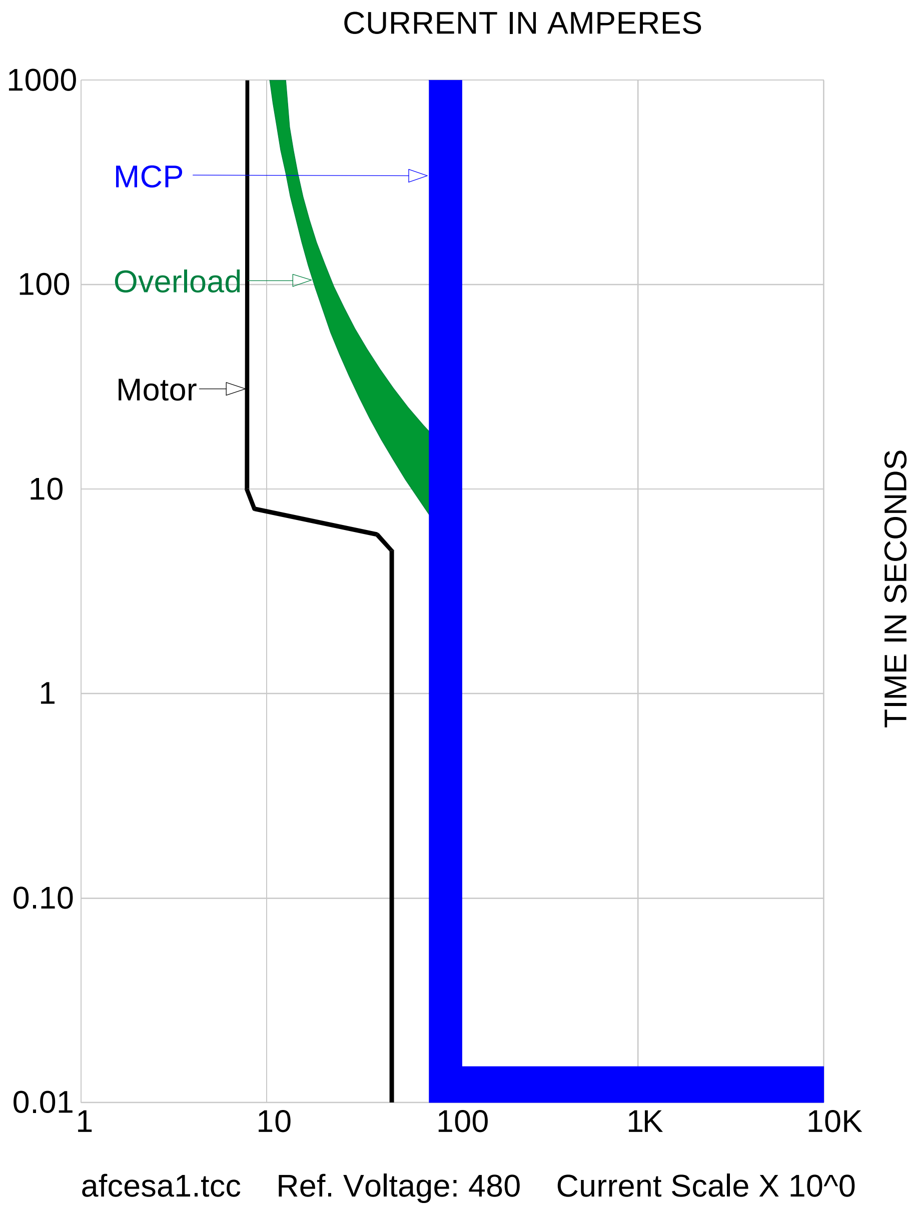
5.1.4. Either thermal-magnetic, magnetic only, or solid-state breakers can be used for motor applications. Magnetic only breakers provide short circuit and high level ground fault protection. This type of breaker must be used with a combination motor starter; the starter provides overload protection for each conductor. The instantaneous trip on the breaker must be adjustable so that it can be set just above the starting current of the motor, within the limits established by NEC Article 430-52 and NEC Table 430-152 (1999 edition). This allows for short circuit protection to be provided for any current slightly above the instantaneous peak starting current of the motor. Figure 5.2 shows this basic arrangement.

Figure 5.2. Combination Motor Starter Protection.



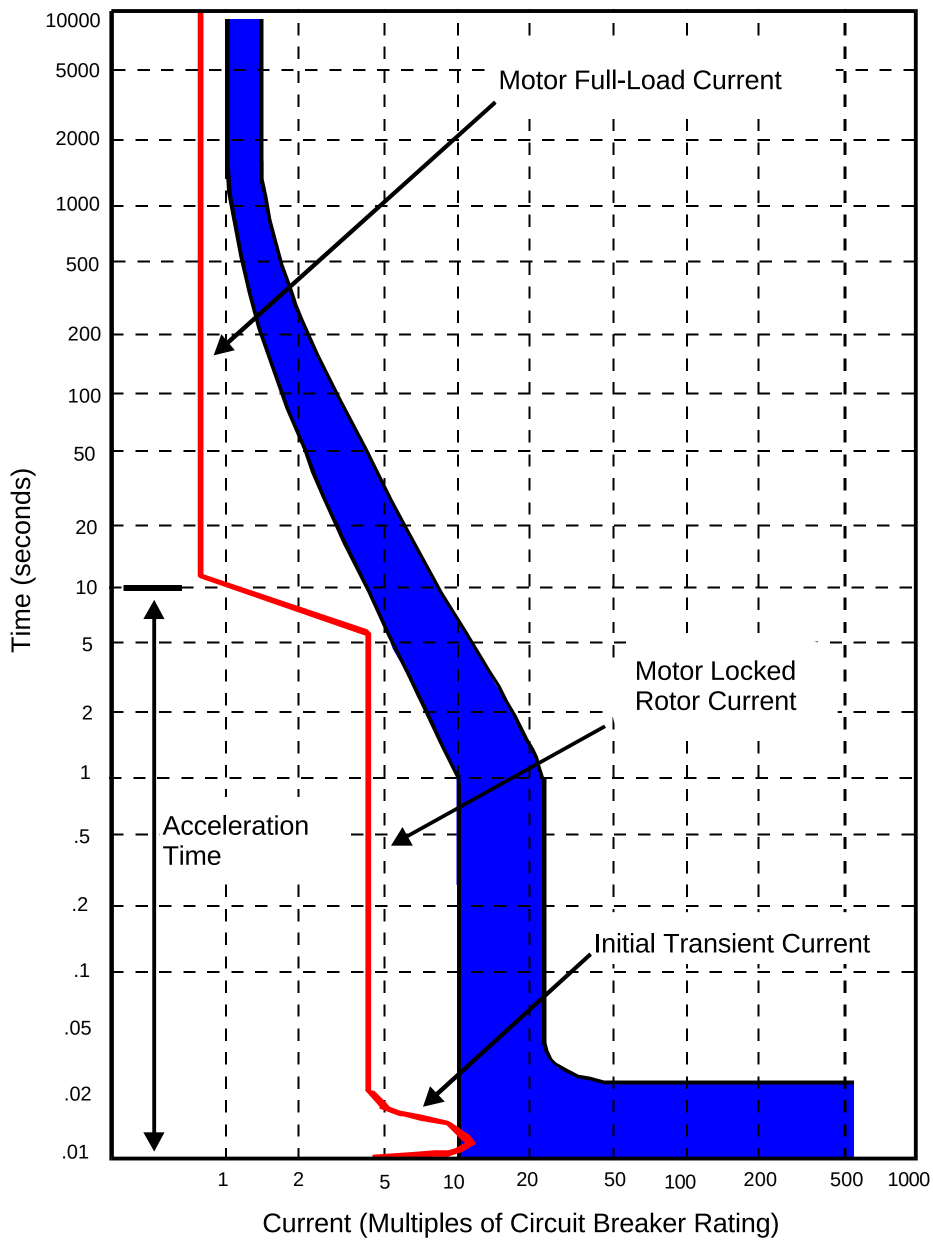
5.1.5. A breaker or other protective device must allow a motor to start, accelerate, and attain its full load current without tripping. Figure 5.3 shows an example set of protective device time-current curves in relation to an example motor starting curve. After a time interval ranging from several cycles to several seconds depending on the motor design and the applied voltage, the current falls to the full load current of the motor. The overload relay and motor circuit protector (MCP) time-current curves must be above and to the right of the motor starting curve. And, whatever protective devices are selected must satisfy both design needs: they must allow the motor to start and run under design conditions, but also must protect the motor from sustained overload or short circuit conditions.

Figure 5.3. Motor Starting Current in Relation to Protective Device Time-Current Curves.



5.1.6. Computer-generated time-current curves will show the motor locked current, usually set about 6 times the motor full load current. But, when voltage is initially applied to a motor, the initial transient current may peak higher than the motor locked rotor current, which is seldom shown on computer-generated time-current curves. As the motor accelerates, the current stabilizes at the locked rotor current of the motor as shown on Figure 5.4. This initial transient current can cause nuisance tripping during starting and it is often not repeatable because the peak depends on the voltage phase angle at the instant of starting. Energy efficient motors can have even higher initial transient currents than standard efficiency motors. This is why the 1999 NEC allows the instantaneous setting for an instantaneous only breaker to be set as high as 17 times the full load current for Design E or Design B energy efficient motors.

Figure 5.4. Motor Starting Current Showing the Initial Transient Current.



5.1.7. Whenever a standard efficiency motor is replaced with an energy efficient motor, evaluate the instantaneous overcurrent protection and adjust the instantaneous trip setting as necessary, within NEC limits, to minimize nuisance trips during starting. If the instantaneous trip setting is adjusted, evaluate the response to the available short circuit current.

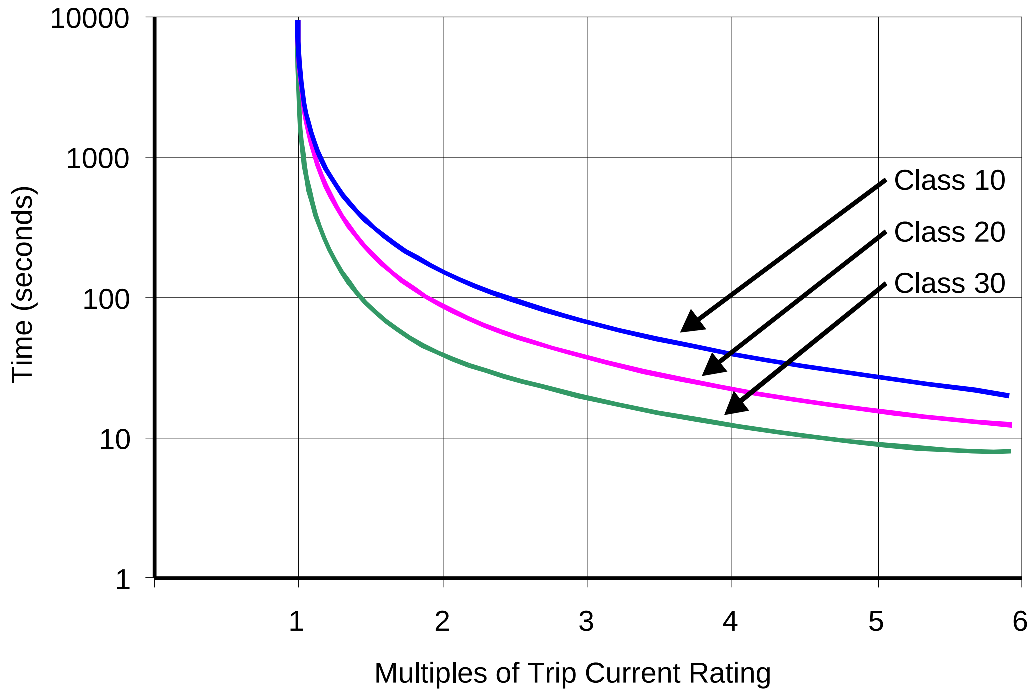
5.2. Overload Protection:

5.2.1. Introduction:

5.2.1.1. A motor can experience an overload condition while running. Although an overload might not draw enough current to actuate short circuit protection (circuit breaker or fuses), an overload can produce sufficient heat to overheat and burn up the motor. The heat generated during an overload condition eventually causes insulation failure.

5.2.1.2. Circuit breakers and fuses are used to protect against overcurrent conditions such as varying levels of short circuit current, but these protective devices are not always suitable for overload protection. In this case, overload relays are used. Overload relays are sized so that they will not open the circuit during motor starting conditions, but do open under overload conditions. As part of motor protection design, overload relays will usually have sufficient time delay to allow temporary overloads (such as motor starting) without opening the circuit. Figure 5.5 shows the approximate time-current characteristics of standard thermal overload relays.

Figure 5.5. Time-Current Characteristics of Standard Thermal Overload Relays.



5.2.2. Overload Relay Selection and Sizing:

5.2.2.1. The overload relay size should be evaluated as part of any motor replacement. A newer energy efficient motor might have different starting and running characteristics than the motor that was replaced. For example, many motors are oversized and underloaded, and a motor might be downsized to a lower horsepower rating as part of an energy efficiency improvement effort. But, the existing motor overload relays can violate NEC protection requirements if a smaller motor is installed. The overload relay design must be evaluated as part of a motor change.

5.2.2.2. NEC Article 430-32 (1999 edition) requires continuous duty motors rated above one horsepower having a marked service factor of not less than 1.15 or a temperature rise not over 104 °F (40 °C) to have overload protection rated for no more than 125 percent of the motor nameplate full-load rating. All other continuous duty motors above one horsepower shall have overload protection rated for no more than 115 percent of the motor nameplate full load rating.

5.2.2.3. Automatically started motors, permanently installed motors, or motors not in sight of the controller location that are rated one horsepower or less have essentially the same requirements as for motors above one horsepower. A non-automatically started motor rated at one horsepower or less is allowed to be protected by the branch circuit short-circuit and ground-fault protective device, provided that it is within sight of the controller and is not permanently installed.

5.2.2.4. Verify that an overload relay is properly sized for the associated motor and then check the overload relay tripping time for the motor's rated locked rotor current. The overload relay tripping time as a function of current should allow sufficient time for the motor to start, accelerate, and reach full speed. The selected overload relay should not actuate throughout the motor's operating current range, from starting current to long term operation at full load current. If the overload relay size is not adequate to start the motor or carry the load, the next higher size overload relay is permitted by the 1999 NEC, provided that it does not exceed the following percentages of motor full load rating:

5.2.2.4.1. 140 percent for motors with a marked service factor of not less than 1.15.

5.2.2.4.2. 140 percent for motors marked with a temperature rise not over 104 °F (40 °C).

5.2.2.4.3. 130 percent for all other motors.

5.2.2.5. If the overload relay is located in a lower ambient temperature than the motor, its time-current rating should be corrected for the lower ambient temperature. The manufacturer can provide the appropriate correction factors.

EXAMPLE: Evaluate the overload protection for the following motor:

50 horsepower, 460 volts
65 amperes full-load current
Locked rotor current = 6 times full-load current
Motor rated for service factor of 1.15 and 40 °C temperature rise
Ambient temperatures: 40 °C at motor and 30 °C at starter
Starter size = NEMA 3
Overload relay: Class 20, 61.3-65.4 amperes continuous rating

Maximum allowable trip unit rating is 125 percent of motor full-load rating, or 125 percent of 65 amperes. Actual trip current is 125 percent of minimum overload relay setting, or 125 percent $\times$ 61.3 = 76.63 amperes. The actual trip rating is 76.63/65 = 118 percent, which is acceptable.

The starter is in a lower ambient temperature than the motor. Assume the manufacturer provides an ambient temperature correction factor of 1.1. The approximate trip current then is 76.63 $\times$ 1.1 = 84.3 amperes. Determine the expected trip time at locked rotor current by determining the multiple of trip current rating, or (6 $\times$ 65)/84.3 = 4.63. Referring to Figure 5.5, the Class 20 overload relay will actuate in about 20 seconds at this current. Verify that the motor will start and accelerate well within this time. A 50 percent safety factor is desirable, or the motor should start within 13 seconds.

5.3. Unbalanced Voltages:

5.3.1. A voltage unbalance occurs when the voltages of a 3-phase supply are not equal. The principal source of a steady-state voltage unbalance is unbalanced single-phase loads on a 3-phase system. Unbalanced voltages can also be caused by blown fuses on one phase of a circuit or single phasing conditions. Even under ideal conditions, a perfectly balanced 3-phase voltage is unlikely because of the following:

5.3.1.1. Single-phase loads are not evenly distributed among the three phases.

5.3.1.2. Single-phase loads are continually connected and disconnected for the electrical system.

5.3.1.3. The 3-phase supply voltage might not be completely balanced.

5.3.2. Voltage unbalance is an important consideration for 3-phase motor loads. ANSI C84.1, *Electrical Power Systems and Equipment—Voltage Ratings (60 Hz)*, specifies a no-load service entrance voltage unbalance of less than 3 percent to avoid motor overheating or failure. Unbalanced voltages cause 3-phase motors to operate at temperatures higher than their rated limits. And, the rate of temperature rise increases with increasing voltage unbalance.

> EXAMPLE: The temperature rise attributed to voltage unbalance can be estimated as follows:
>
> $$Temperature\ Rise\ (°C) = 2 \times (Percent\ \ Unbalance)^2$$
>
> If the percent voltage unbalance is 4 percent, the expected temperature rise associated with this unbalance is:
>
> $$Temperature\ Rise\ (°C) = 2 \times (4\%)^2 = 32°C$$
>
> A common rule of thumb is that every 18 °F (10 °C) reduces expected motor life by 50 percent. A temperature rise of 36 °F (20 °C) caused by voltage unbalance can reduce expected motor life by 75 percent.

5.3.3. High efficiency motors are particularly susceptible to unbalanced voltages; these motors have a lower negative sequence reactance which causes higher negative sequence currents during unbalanced voltage conditions.

5.3.4. A motor operating in an unbalanced circuit cannot deliver its rated horsepower and the rated load capability of 3-phase motors is reduced when voltage unbalance is present. Figure 5.6 shows the internal temperature rise of motors as a function of percent voltage unbalance. Figure 5.7 shows a derating factor for 3-phase induction motors as a function of voltage unbalance. As can be seen, unbalanced voltages can have a significant effect on motor operation and life.

Figure 5.6. Voltage Unbalance Effect on Temperature Rise of Three-Phase Motors.

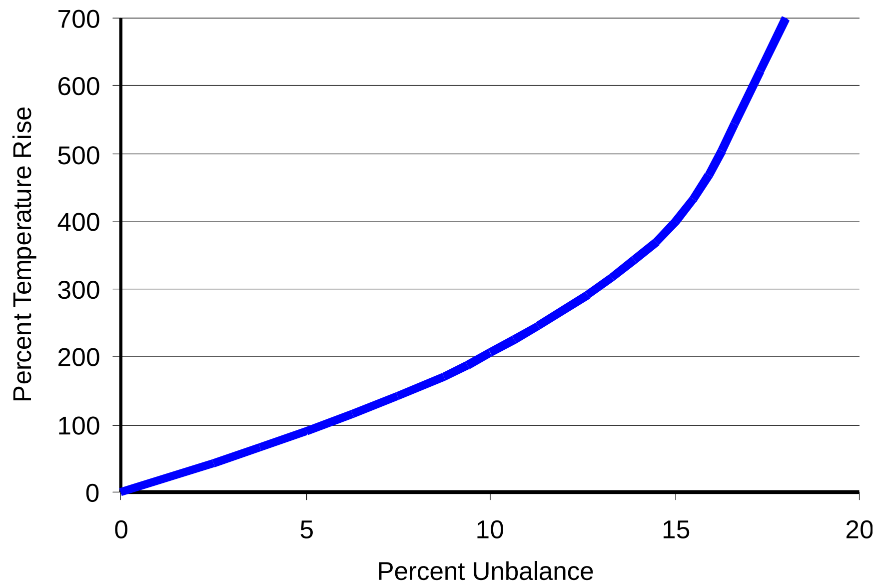
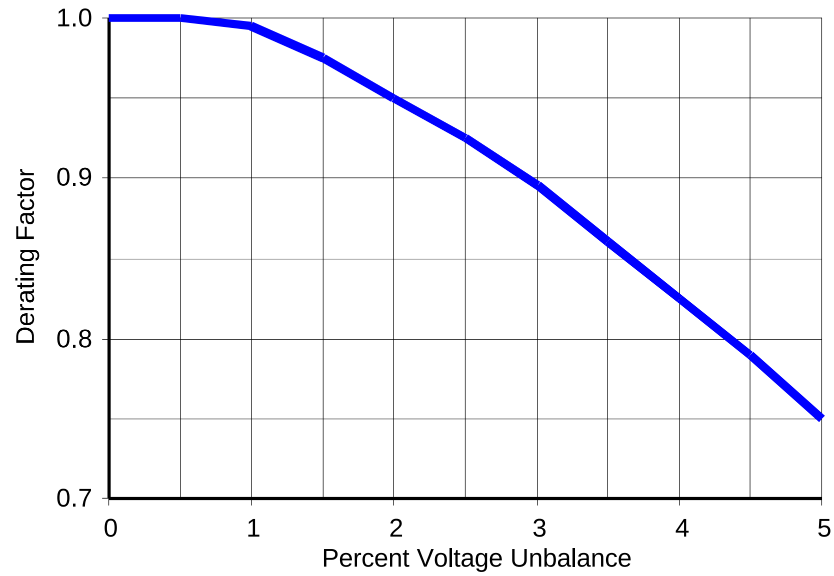


Figure 5.7. Derating Factor for Three-Phase Induction Motors.



5.3.5. ASDs are also sensitive to voltage unbalance. As the amount of voltage unbalance increases, the ASD phase current unbalance can be significantly higher. For example, even if the ANSI C84.1 recommended limit of 3 percent voltage unbalance is met, the ASD current unbalance might be higher than 50 percent, which can actuate some overload protection. ASDs also generate more harmonic currents with increasing voltage unbalance, including third harmonic current. The magnitude of current unbalance also depends on the ASD loading, the dc link capacitor size, and the line impedance. Evaluate the voltage and current unbalance as part of any ASD installation to ensure that the ASD performance will be acceptable. If an ASD periodically trips off-line, evaluate the degree of current unbalance to determine if it is potentially actuating overload protection. If the voltage unbalance cannot be corrected by redistributing single-phase loads, it might be necessary to install filter reactors to improve the current unbalance (refer to paragraphs 4.3.5 through 4.3.5.5).

5.3.6. A commonly used method of evaluating voltage unbalance is as follows:

$$Percent\ Unbalance = \frac{Maximum\ Phase\ Deviation\ from\ Average\ Voltage}{Average\ Voltage} \times 100\%$$

EXAMPLE: Assume that phase voltages are 460, 464, and 450. The average phase voltage is 458. The maximum deviation from the average voltage is 8 volts and the percent unbalance is given by: $$Percent\ Unbalance = \frac{8}{458} \times 100\% = 1.75\%$$

5.3.7. Notice that the above method of calculating percent unbalance is based on easily taken electrical measurements. If the percent unbalance exceeds 2 percent, evaluate the electrical system in more detail to determine if corrective action is necessary.

5.4. ASD Protection:

5.4.1. ASD installations must comply with NEC requirements for overcurrent protection. If a bypass is provided with the ASD, the bypass must be provided with all NEC required protection. Refer to paragraphs 4.2.4 through 4.2.4.6 for additional information.

5.4.2. Other ASD design features for protection against voltage transients, harmonics, and other power quality problems are described in Chapter 4.

Chapter 6

COMMISSIONING

6.1. Motor Commissioning:

6.1.1. Motors and motor control circuits should be inspected and tested in accordance with NETA ATS-1991, *Acceptance Testing Specifications for Electrical Power Distribution Equipment and Systems*.

6.1.2. If the motor was installed as part of an energy efficiency improvement effort, monitor the motor running current to confirm that the expected energy savings have been achieved.

6.2. ASD Commissioning:

6.2.1. An ASD installation should be completely inspected and tested to ensure that standard electrical safety requirements have been met.

6.2.2. An ASD requires a careful checkout to ensure that it operates as expected. The manufacturer's installation and startup manual should provide specific guidance for verifying the proper operation of the ASD. The interfaces to the external control signals must be verified to operate properly and ASD output functions must be checked.

6.2.3. After the ASD is programmed and fully prepared for operation, the motor should be connected and started from the ASD. Motor operation with the normal control signal should be confirmed. The motor speed should be checked from minimum speed to full speed. The motor should be started with full load applied to confirm that the ASD is capable of accelerating and running the motor.

6.2.4. The power or current input to the ASD should be monitored as part of commissioning to confirm that the expected energy savings have been achieved.

6.3. Power Quality Monitoring:

6.3.1. Because an ASD can affect the power quality of the electrical system, power quality monitoring should be performed with and without the ASD operating to determine its impact on the electrical system.

6.3.2. Refer to IEEE 1159, *IEEE Recommended Practice for Monitoring Electric Power Quality*, for guidance regarding power quality measurements.

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DCS/Installation & Logistics

Attachment 1

GLOSSARY OF REFERENCES AND SUPPORTING INFORMATION

References

Note: The most recent edition of referenced publications applies, unless otherwise specified.

Air Force Publications:

AFI 32-1080, *Electric Power Systems*
AFMAN(I) 32-1181, *Design Standards for Facilities Interior Electrical Systems*
AFMAN(I) 32-1281, *Facilities Engineering, Electrical Interior Facilities*
AFMAN(I) 32-1280, *Facilities Engineering, Electrical Exterior Facilities*

Federal Regulations:

Energy Policy Act of 1992 (EPACT)
Executive Order (EO) 12902, *Energy Efficiency and Water Conservation at Federal Facilities,* dated March 8, 1994
EO 13123, *Greening the Government Through Efficient Energy Management*, dated June 3, 1999
10 CFR Part 435, *Energy Conservation Voluntary Performance Standards for New Buildings: Mandatory for Federal Buildings*
10 CFR Part 436, *Federal Energy Management and Planning Programs*
48 CFR Part 23.704, *Federal Contracting Preference Programs for Environmentally Preferable and Energy Efficient Products and Services*

ANSI and IEEE Standards:

ANSI C2-1997, *National Electrical Safety Code*
ANSI C84.1-1995, *Electrical Power Systems and Equipment—Voltage Ratings (60 Hz)*
IEEE 112-1996, *IEEE Standard Test Procedure for Polyphase Induction Motors and Generators*
IEEE 141-1993, *Electric Power Distribution for Industrial Plants* (IEEE Red Book)
IEEE 241-1990, *Electric Power Systems in Commercial Buildings* (IEEE Gray Book)
IEEE 242-1986 (R1991), *Protection and Coordination of Industrial and Commercial Power Systems* (IEEE Buff Book)
IEEE 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*
IEEE 1015-1997, *Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems* (IEEE Blue Book)
IEEE 1100-1992, *Powering and Grounding Sensitive Electronic Equipment* (IEEE Emerald Book)
IEEE 1159-1995, *IEEE Recommended Practice for Monitoring Electric Power Quality*

NEMA Standards:

NEMA ICS 1-1993, *Industrial Control and Systems: General Requirements*
NEMA ICS 2-1993, *Industrial Control and Systems: Controllers, Contactors and Overload Relays, Rated Not More Than 2000 Volts AC or 750 Volts DC*
NEMA ICS 3.1-1990, *Safety Standards for Construction and Guide for Selection, Installation, and Operation of Adjustable-Speed Drive Systems*

NEMA ICS 7-1993, *Industrial Control and Systems: Adjustable Speed Drives*

NEMA MG1-1993, *Motors and Generators*

NEMA MG-10-1994, *Energy Management Guide for Selection and Use of Polyphase Motors*

NEMA MG-11-1977 (R1992), *Energy Management Guide for Selection and Use of Single-Phase Motors*

NETA Specifications:

NETA ATS-1991, *Acceptance Testing Specifications for Electrical Power Distribution Equipment and Systems*

NETA MTS-1993, *Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems*

NFPA Standards:

NFPA 70-1999, *National Electrical Code*

DOE Motor Challenge and Related Documents:

Buying Energy Efficient Products, Federal Energy Management Program

DOE/GO-10096-248, *Measurement and Verification (M&V) Guideline for Federal Energy Projects*

DOE/RL/01830P-H4, *Architect's and Engineer's Guide to Energy Conservation in Existing Buildings, Volume 2—Energy Conservation Opportunities*

Electric Motor Model Repair Specifications, Washington State Energy Office

Energy Efficient Electric Motor Selection Handbook, G. McCoy and J. Douglass

Energy Management for Motor Driven Systems, G. McCoy and J. Douglass

Industrial Motor Repair in the United States, V. Schueler, P. Leistner, and J. Douglass

Industrial Electrotechnology Laboratory Horsepower Bulletin

Motor Challenge Sourcebook, including associated documents and computer programs

MotorMaster User Guide

Quality Electric Motor Repair: A Guidebook for Electric Utilities, V. Schueler and J. Douglass

> *Note: The above Motor Challenge and related documents are available through the DOE Motor Challenge Program. Contact the Motor Challenge Program Information Clearinghouse at PO Box 43171, Olympia, Washington, 98504-3171, or by telephone at 800-862-2086.*

Miscellaneous Documents:

Electrical Apparatus Service Association (EASA), *EASA Standards for the Repair of Electrical Apparatus*

Energy-Efficient Electric Motors and Their Applications, H. Jordan, Second Edition

Energy-Efficient Electric Motors, Selection and Application, J. Andreas, Second Edition

EPRI AP-106949, Edition 0, *ASDMaster User's Manual*, and Edition 1, *ASDMaster User's Guide*

EPRI TR-101140, *Adjustable Speed Drives—Applications Guide*

EPRI TR-101536-V1, *Power Quality for Electrical Contractors, Applications Guide, Volume 1: Power Quality Fundamentals*

EPRI TR-101536-V2, *Power Quality for Electrical Contractors, Applications Guide, Volume 1: Recommended Practices*

Handbook of Energy Engineering, A. Thumann and D. Mehta, Fourth Edition

Motor Application and Maintenance Handbook, R. Smeaton, Second Edition

Technical Manual TM 5-811-13, *Standards and High-Efficiency Motors and Controllers*

Abbreviations and Acronyms

ac—Alternating Current

AFCESA—Air Force Civil Engineer Support Agency

AFMAN—Air Force Manual

AFPAM—Air Force Pamphlet

ANSI—American National Standards Institute

ASD—Adjustable Speed Drive

CFM—Cubic Feet Per Minute

CFR—Code of Federal Regulations

CSI—Current Source Inverter

dc—Direct Current

DLA—Defense Logistics Agency

DOE—Department of Energy

EASA—Electrical Apparatus Service Association

EMF—Electromagnetic Force

EO—Executive Order

EPACT—Energy Policy Act of 1992

EPRI—Electric Power Research Institute

ESPC—Energy Savings Performance Contracts

EXPL—Explosion Proof

FAR—Federal Acquisition Regulations

g—Acceleration of Gravity

GSA—General Services Administration

hp—Horsepower

HVAC—Heating, Cooling, and Ventilation

hz—Hertz

I—Amperes

IEC—International Electrotechnical Commission

IEEE—Institute of Electrical and Electronics Engineers

IGBT—Insulated Gate Bipolar Transistor

ISO—International Standards Organization

kW—Kilowatts

kWh—Kilowatt Hours

kVA—Kilovolt-Amperes

kVAR—Kilovolt-Amperes Reactive

LF—Load Factor

LVPB—Low Voltage Power Breaker

MCC—Motor Control Center

MCCB—Molded Case Circuit Breaker

MCP—Motor Circuit Protector

M/G—Motor Generator

MTBF—Mean Time Between Failure

MTTR—Mean Time to Repair

MVA—Megavolt-Amperes

NEC—National Electrical Code

NEMA—National Electrical Manufacturers Association

NETA—International Electrical Testing Association

NFPA—National Fire Protection Association

O&M—Operations and Maintenance

ODP—Open Drip Proof

OEM—Original Equipment Manufacturer

OL—Overload

OMB—Office of Management and Budget

p—Pressure

PCC—Point of Common Coupling

PF—Power Factor

PLC—Programmable Logic Controller

PWM—Pulse Width Modulation

rpm—Revolutions Per Minute

SCR—Silicon Controlled Rectifier

TEFC—Totally Enclosed Fan Cooled

TENV—Totally Enclosed Non-Ventilated

THD—Total Harmonic Distortion

UPS—Uninterruptible Power Supply

V—Volt

Vac—Volts Alternating Current

VAV—Variable Air Volume

Vdc—Volts Direct Current

VFD—Variable Frequency Drive (see ASD)

VSI—Variable Source Inverter

VVI—Variable Voltage Inverter

Terms

> *Note: The terms listed here are provided for clarification of the design criteria provided in this pamphlet. Refer to IEEE 100,* IEEE Standard Dictionary of Electrical and Electronics Terms, *for additional electrical-related definitions.*

***Acceleration Torque*—**The amount of torque needed to accelerate the load from one speed to a higher speed within a given time.

***Adjustable Speed Drive*—**An electronic equipment that controls the speed of a motor by adjusting the frequency of the motor's power supply. Some adjustable speed drives also control current and phase angle to control other elements of motor performance.

***Affinity Curve*—**A parabolic curve drawn through a particular flow and head point and the origin. See Affinity Laws.

***Affinity Laws*—**A set of relationships in fluid dynamics that predicts how changes in size, power, pressure, flow, speed, and efficiency relate to each other in a dynamic-displacement pump.

***Ambient Temperature*—**The temperature of the surrounding air.

***Branch Circuit*—**The portion of a distribution system between the final overcurrent protection device and the load connected to it.

***Breakaway Torque*—**The amount of torque required to break the load away from rest and start the load in motion.

***Breakdown Torque*—**The maximum torque a motor will produce and is also referred to as maximum torque and pull-out torque.

Bypass**—**The ability to start a motor directly across the incoming electric supply rather than via the ASD. Bypass capability provides the ability to start and operate a motor in the event of ASD failure.

Constant Power**—**A driven load for which shaft power is maintained at a controlled or preset level for a range of operating speeds.

Constant Torque**—**A driven load for which load torque is maintained as a controlled or preset level for a range of operating speeds.

Contactor**—**A control device that uses a small control current to energize or deenergize the load connected to it.

Continuous Duty **—**Operation at a substantially constant load for an indefinitely long time.

Cube Law**—**A result of the affinity laws in which power is related to the cube of flow rate under certain conditions.

Current Source Inverter**—**The ASD provides a stepped current waveform to the motor.

Driven Load**—**The machine or equipment that the motor is driving.

Dual Redundancy**—**With regard to ASDs, it applies to a system with two fully rated ASDs that each can be used to control a single motor. The system can be connected such that either ASD can fail or be taken out of service without losing control of the load.

Efficiency**—**The ratio of output power to input power, with a value somewhere between 0 and 1.

Enclosure, Open Drip Proof (ODP)**—**A motor enclosure design that allows outside air to blow directly through the motor, but has a cover that prevents drops of liquid from entering. ODP motors are suitable for protected environments.

Enclosure, Totally Enclosed Fan Cooled (TEFC)**—**A motor enclosure design that prevents outside air from flowing into the frame. Cooling of TEFC motors is provided by fins and a fan. TEFC motors are suitable for outdoor use, and in dusty or contaminated environments.

Enclosure, Totally Enclosed Nonventilated (TENV)**—**A motor enclosure design that is not equipped for cooling by means external to the enclosing parts.

Enclosure, Explosion Proof (EXPL)**—**A type of TEFC motor enclosure design that is designed to prevent sparks or explosions within the motor from igniting flammable materials outside.

Energy Efficient Motor**—**A motor with a nominal full-load efficiency rating that meets or exceeds the efficiency specified in NEMA MG1 Table 12-10. Manufacturers also sell motors with efficiencies significantly higher than the NEMA standard and designate these as high- or premium-efficiency motors.

Equipment Curve**—**A graphical description of the pressure that will be developed across a pump over a range of flow rates. Equipment curves commonly show shaft power or efficiency.

Flow Control**—**The act of or ability to continuously adjust the flow rate of a fluid stream in response to some external parameter(s) or in accordance with preprogrammed instructions.

Frame Size**—**NEMA-defined standard motor frame dimensions. Select a motor with the same frame size as the existing motor, unless the motor mount will also be modified.

Friction and Windage**—**The power loss within any rotating electrical machine caused by bearing friction, air friction against rotating surfaces, and the movement of air circulating fans.

Full Load Current**—**The current required by the motor to produce full load torque at the motor's rated speed.

Full Load Speed**—**The speed at which rated horsepower is developed.

Full Load Torque**—**The torque required to produce rated horsepower at full load speed.

Harmonic Content**—**The difference between the actual voltage/current waveform and a pure sine wave.

Horsepower**—**A unit of measure for the power of motors. One horsepower equals 746 watts.

Induction Motor**—**The most common type of industrial motor.

Inrush Current**—**The high current drawn by a motor during startup.

Insulation**—**Non-conducting materials separating the current-carrying parts of a motor from each other and the core.

Intermittent Duty **—**Operation for alternate intervals of 1) load and no load, or 2) load and rest, or 3) load, no load, and rest.

Jogging**—**Frequent starting and stopping of a motor for short periods of time.

Load Duty Cycle**—**A tabular or graphical description of the variability of flow or load over time.

Load Factor**—**A measure of the ratio between a motor's operating output and its design output. For example, a 10 horsepower motor driving a 5 horsepower load has a 50 percent load factor.

Load Torque**—**The torque required by a driven load to achieve or maintain a given speed.

Locked Rotor Current**—**The current drawn by a motor with the rotor stopped (locked) and full voltage applied.

Locked Rotor Torque**—**The torque produced by a motor when the rotor is stationary and full power is applied to the motor.

Lockout**—**The process of removing the source of electrical power and installing a locking device to prevent the power from being turned on.

Losses**—**Energy that is not transmitted through a machine in a useful form.

Low Voltage**—**A voltage rating 600 volts or less.

Magnetic Motor Starter**—**A contactor that includes motor overload protection.

Manual Contactor**—**A control device that uses pushbuttons or similar device to energize or deenergize the connected load.

Medium Voltage**—**A voltage rating above 600 volts.

Motor**—**A machine that converts electrical energy into mechanical energy.

Overload**—**A condition that exceeds the rated load for a specified period. Typically, fans and pumps are provided with an overload capability of 115 percent for one minute. Motor circuits are provided with overload protection in which the allowed duration of the overload varies with the amount of overload.

Overload Relay**—**A protective device that responds to an overload condition by opening the circuit connection to the load.

Overspeed**—**The operating speed range above rated speed. A motor can typically be operated up to 20 percent above rated speed.

Part-Winding Starting**—**A method of starting a motor by first applying power to part of motor coil windings for starting and then applying power to the remaining coil windings for normal running.

Payback**—**The time period at which the added cost of a more efficient motor or other equipment equals the operating cost savings obtained by its use.

Peak Torque**—**Occasional peak torque required by the load, such as a large weight being dropped on a conveyor.

Percent Slip**—**The percentage reduction in speed below synchronous speed.

Periodic Duty **—**Intermittent operation in which the load conditions are regularly concurrent.

Poles**—**The number of magnetic poles set up inside the motor by the placement and connection of the windings.

Primary Resistor Starting**—**A reduced voltage starting method which uses a resistor connected in each motor line to produce a voltage drop.

Rectifier**—**A circuit that converts ac to dc.

Rated Temperature Rise**—**The permissible temperature rise above ambient temperature for a motor operating under load.

Ride Through**—**An ASD term defining its ability to operate through a temporary power failure or momentary power disturbance.

Rotor**—**The rotating element in a motor.

Running Torque**—**The torque required to maintain the drive process or machine after it accelerates to the desired operating speed.

Sag**—**A decrease in voltage outside the normal tolerance that lasts for 2 seconds or less. Sags are caused by starting of large motors or system faults.

Service Factor**—**A factor that defines the amount that a motor can be loaded beyond its horsepower rating without suffering insulation damage. A service factor of 1.15 is common.

Shaft Power**—**The mechanical power transmitted from the motor shaft to the driven load.

***Short-Time Duty* —**Operation at a substantially constant load for a short and definitely specified time.

Single-Phasing**—**The operation of a motor that is designed to operate on 3 phases, but is only operating on two phases because one phase is lost.

Single Voltage Motor**—**A motor that operates at only one voltage level.

Slip**—**The percentage difference between synchronous and operating speeds.

Snubber Circuit**—**A circuit that suppresses noise and high voltage spikes.

Speed Control**—**The ability to maintain speed despite changing torque conditions.

Split-Phase Motor**—**A single phase ac motor that includes a running winding (main winding) and a starting winding (auxiliary winding).

Starting Torque**—**The torque produced by a motor at rest when power is applied.

Stator**—**The stationary element in a motor.

Swell**—**An increase in voltage outside the normal tolerance that lasts for 2 seconds or less. Swells are usually caused by the sudden decrease or loss of large loads.

Synchronous Speed**—**The maximum speed for an ac motor, given by

$$Synchronous\ \ Speed\ \ (rpm) = \frac{Frequency \times 120}{Number\ \ of\ \ Poles}$$

Torque—The rotating force produced by a motor.

Variable Torque—A driven load for which load torque changes nonlinearly with shaft speed.

Varying Duty —Operation at loads, and for intervals of time, both of which can be subject to wide variation.

Voltage Unbalance—The unbalance that occurs when the voltages at different motor terminals are not equal. Also referred to as phase unbalance.

Attachment 2

MOTOR INVENTORY DATA

A2.1. Manual Inventories:

A2.1.1. An accurate motor inventory is needed for the purpose of prioritizing motor replacements to achieve energy savings. An inventory will also help facilitate motor repair and replacement activities.

A2.1.2. Table A2.1 provides an example of data in a motor inventory. The information shown in this table is needed to determine an adequate replacement and to calculate the expected energy savings. Table A.2.1 is only an example; any format can be used. Documents available from the DOE Motor Challenge Program provide other examples of data for motor inventories.

Table A2.1. Example Manual Motor Inventory Data.

Facility Information	
Facility: AFCESA	Motor ID Number: HVAC-1
Machine Description: HVAC Fan	Installation Date: 02/98
Department: CESE	Maintenance History:
Operating Hours:	
shifts/day: 3	
days/week: 7	
Load Type: Centrifugal	
Location: 3B/12	
Nameplate Information	
Manufacturer: Baldor	Type: Induction
Frame Designation: 286T	Mount: Standard
Model: SUPER-E	Serial Number: 2342A
Rated Voltage: 460	Number of Phases/Hertz: 3/60
Full Load Amperes: 34.0	Full Load rpm: 1,780
kVA Code: G	NEMA Enclosure Type: TEFC
NEMA Design: B	Insulation Class: F
Nameplate Efficiency: 94.1	Temperature Rise: 311 °F (155 °C)
Time Rating: N/A	Service Factor: 1.15
Thermal Protection? MCC	Power Factor (Full Load): 84.0
Motor Running and Starting Information	
Line to Line Voltage: 472	Locked Rotor Amperes: 214
Phase Currents: 33.9/34.0/34.0	
Measured rpm: 1,776	
Number of Leads: 6 (wound for 230/460)	Notes: Rated for inverter duty
Type of Starting: Full voltage	

A2.2. MotorMaster® Inventories:

A2.2.1. MotorMaster® provides a software-controlled method of maintaining a motor inventory and is recommended. Facility, motor nameplate, operating profile, load status, and field measurement data can be entered.

A2.2.2. Figure A2.1 shows an example MotorMaster® screen with motor nameplate data entered. Figure A2.2 shows the MotorMaster® screen for field measurements; notice that the motor voltage unbalance, motor load factor, and cost of energy usage are automatically calculated.

Figure A2.1. MotorMaster® Inventories.

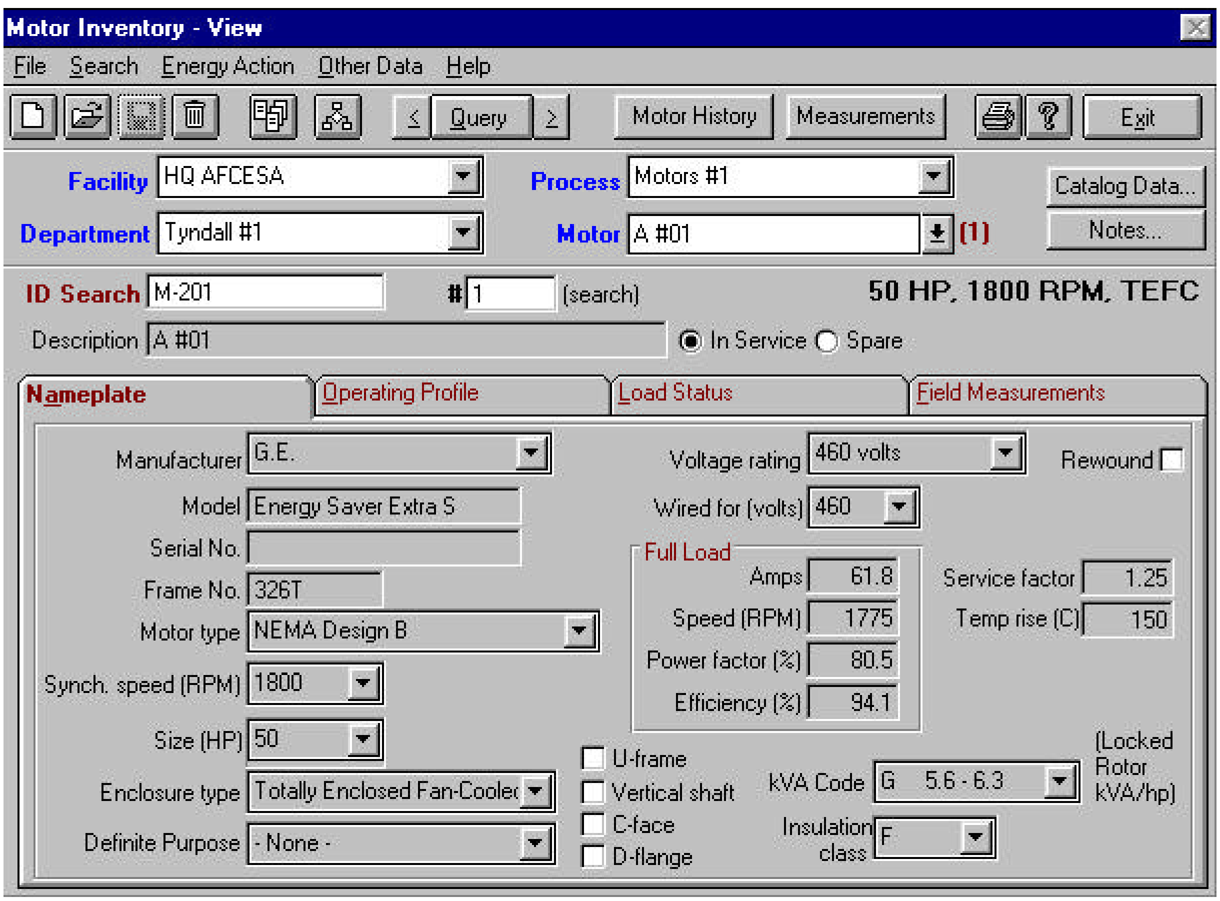

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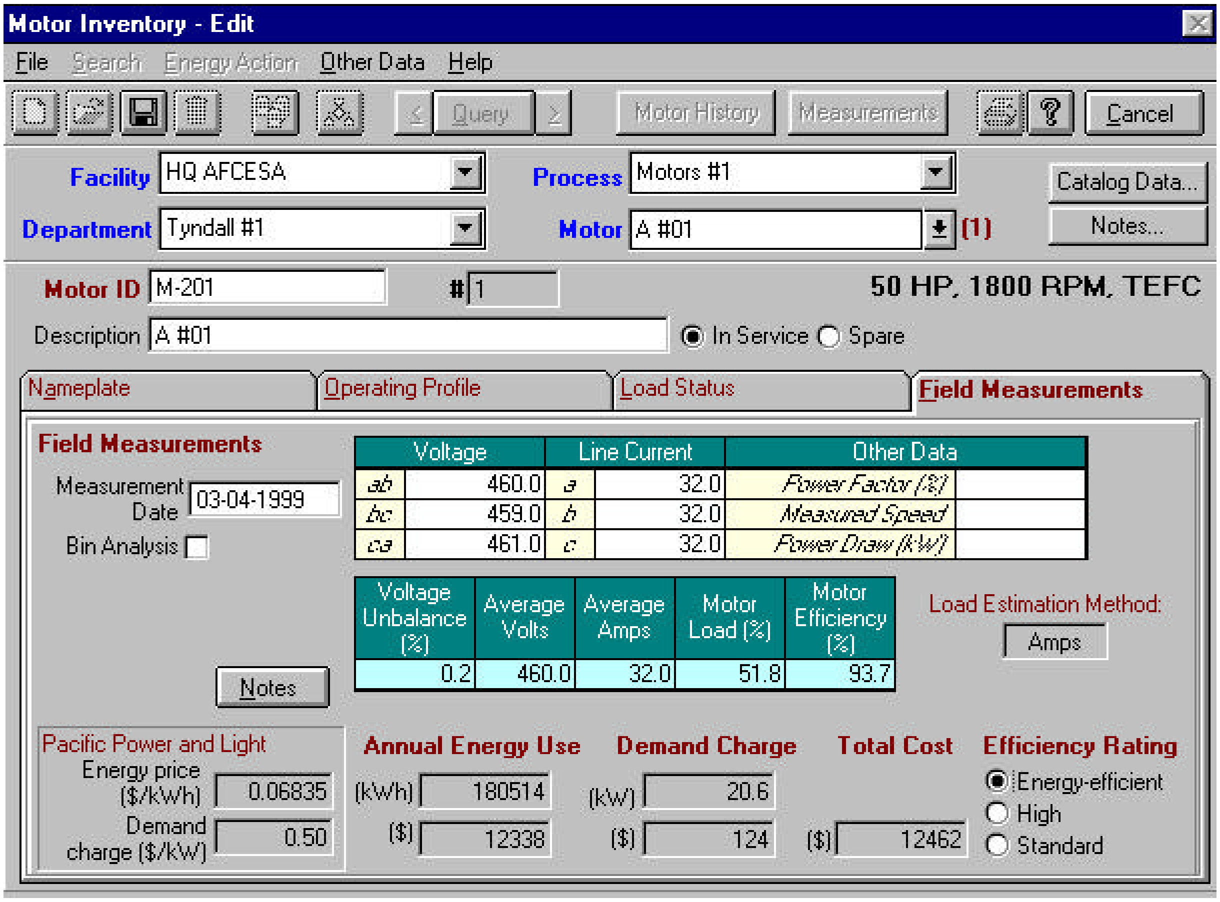
Figure A2.2. MotorMaster® Inventory of Field Measurements.



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Attachment 3

REDUCED VOLTAGE MOTOR STARTING METHODS

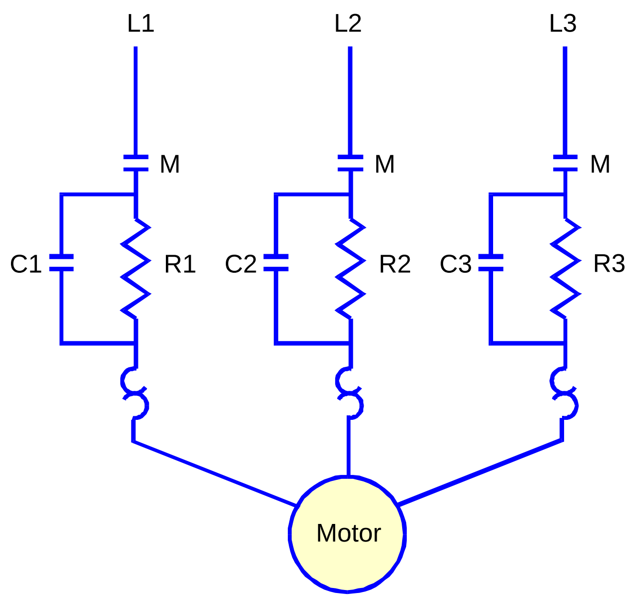
A3.1. Primary Resistor Starting:

A3.1.1. Primary resistor starting is a reduced voltage starting method that uses a resistor connected in each motor phase to produce a voltage drop during starting. This reduces the motor starting current as it passes through the resistor. The associated control circuit closes contacts that bypass the resistors after the motor has accelerated to the specified speed. By this approach, the motor is started at reduced voltage, but operates at full line voltage.

A3.1.2. Primary resistor starters provide smooth starting because the voltage increases across the motor terminals as the motor accelerates. Standard primary resistor starting circuits have a single resistor in each phase with the voltage reduced to approximately 70 percent of line voltage upon motor starting. Multiple steps can be obtained in which additional resistance is progressively removed from the circuit as the motor accelerates.

A3.1.3. The control circuit for primary resistor starting is relatively simple as shown in Figure A3.1. When the motor starter is energized, the M contacts are closed, thereby applying voltage to the motor through resistors R1, R2, and R3. Another M contact closes and actuates a timer. After the timer delay, it closes contacts C1, C2, and C3 to bypass the resistors. The resistor size and wattage is usually selected based on the motor horsepower.

Figure A3.1. Primary Resistor Method Simplified Starting Circuit.



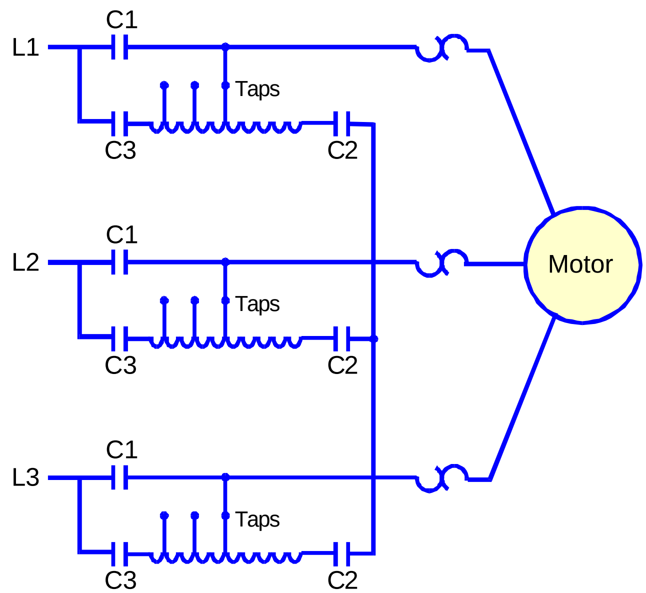
A3.2. Autotransformer Starting:

A3.2.1. Autotransformer starting uses a tapped 3-phase autotransformer to provide reduced voltage starting. Autotransformer starting is preferred over primary resistor starting when the motor starting current must be held to a minimum limit, but the maximum starting torque per line ampere is needed. During autotransformer starting, the various transformer windings are added to and taken away from the motor circuit to provide reduced voltage while starting.

A3.2.2. With an autotransformer, the motor terminal voltage does not depend on the load current. Although the current to the motor will change because of the motor's changing characteristics during starting, the voltage to the motor remains relatively constant. In autotransformer starting, the transformer motor current and the line current are not equal as they are in primary resistor starting. Instead, the autotransformer turns ratio is used to provide more current on the load side than on the line side. Autotransformer starting is usually able to provide more starting torque than primary resistor starting, which can be important for motors with a substantial load.

A3.2.3. Figure A3.2 shows an example of a simplified autotransformer starting circuit. When the motor starting circuit is initially energized, contacts C2 and C3 are closed to energize the motor through the transformer circuit. Different taps are usually provided in the autotransformer to allow user control of the motor starting current. After a specified time delay, contact C1 closes and contacts C2 and C3 open, thereby placing full line voltage across the motor.

Figure A3.2. Autotransformer Method Simplified Starting Circuit.



A3.2.3. Two types of autotransformer control schemes are used: open circuit transition and closed circuit transition. Open circuit transition momentarily disconnects the motor from the circuit as the autotransformer incrementally adjusts voltage. Closed circuit transition maintains voltage to the motor as it adjusts the output voltage. Closed circuit transition produces the least disturbance to the electrical system, but is also more expensive.

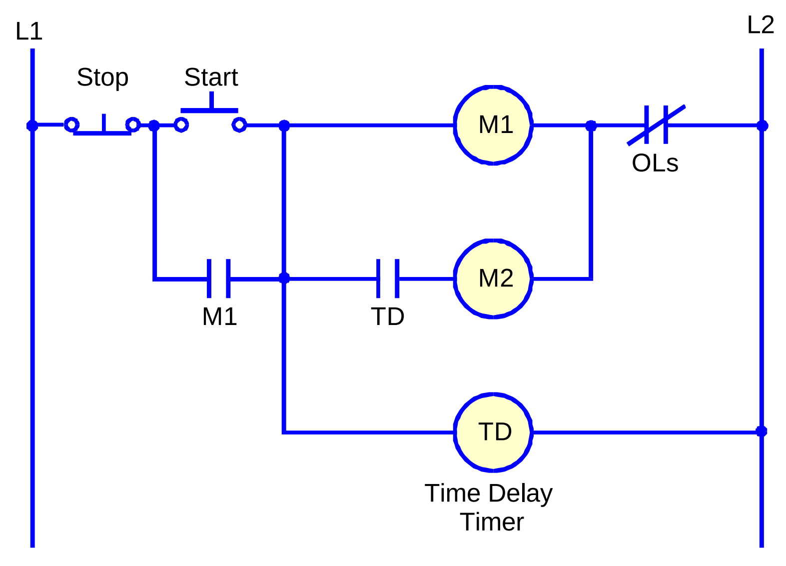
A3.3. Part-Winding Starting:

A3.3.1. Part winding starting is a method of starting a motor by first applying power to part of a motor's coil windings for starting and then applying power to the remaining coil windings for running. Part-winding starting is not actually a reduced voltage starting method, but it is classified as reduced voltage starting because of the reduced current and torque during starting. In most applications, a wye-connected motor is used, but a delta-connected motor can also be started using part-winding starting.

A3.3.2. Part-winding starting requires the use of a part-winding motor. A part-winding motor has two sets of identical windings that are designed to be used in parallel. The windings then produce reduced starting current and reduced starting torque when energized in sequence. Most dual voltage 230/460 volt motors are suitable for part-winding starting.

A3.3.3. Part-winding control circuits are commonly designed such that one winding of the motor is connected directly to line voltage upon starting. This winding draws about 65 percent of rated locked rotor current and develops approximately 45 percent of normal motor torque. After about one second, the second winding is connected in parallel with the first winding so that the motor is electrically complete across the line and it develops its normal torque. Figure A3.3 shows a simplified control circuit. Upon motor starting, M1 energizes starter M1 for the first winding. A contact from M1 energizes the time delay timer, which then energizes M2 after the specified time delay. The motor now has both sets of windings connected to the line for full current and torque. Notice that each magnetic motor starter need be only half-size because it controls only half the winding.

Figure A3.3. Part-Winding Starting Method Simplified Control Circuit.



A3.3.4. Part-winding starting is less expensive than most other methods because it requires no voltage-reducing components such as transformers or resistors, and it uses only two half-size contactors. But, part-winding starting has poor starting torque. Always consult the manufacturer's specifications before applying part-winding starting to a motor.

A3.4. Wye-Delta Starting:

A3.4.1. Wye-delta starting accomplishes reduced voltage starting by first connecting the motor leads into a wye configuration for starting. A motor started in a wye configuration receives approximately 58 percent of the normal line voltage and develops approximately 33 percent of normal torque.

A3.4.2. Wye-delta motors are specially wound with six leads extending from the motor to enable the windings to be connected in either a wye or a delta configuration. When a wye-delta starter is energized, two contactors close, with one contactor connecting the windings in a wye configuration, and the second contactor connecting the motor to line voltage. After a time delay, the wye contactor opens (momentarily deenergizing the motor) and a third contactor closes to reconnect the motor in a delta configuration. This is an open transition system because the motor leads are disconnected and reconnected as the motor is switched from a wye to a delta connection.

A3.4.3. Wye-delta starting does not require additional voltage reducing components such as resistors or transformers. Also, it produces a higher starting torque per line ampere than part-winding starting, with less noise and vibration.

A3.4.4. The open transition transfer from wye to delta operation is the principal disadvantage of this method. Closed transition designs are available at higher cost. Closed transition design is often accomplished with an additional contactor and resistor bank to maintain the motor windings energized for the period of transfer from wye to delta.

A3.5. Solid-State Starting:

A3.5.1. Solid-state starting uses a silicon controlled rectifier (SCR) that controls motor voltage, current, and torque during acceleration. This type of starting can provide a smooth, stepless acceleration of the driven load, which is useful for many industrial applications.

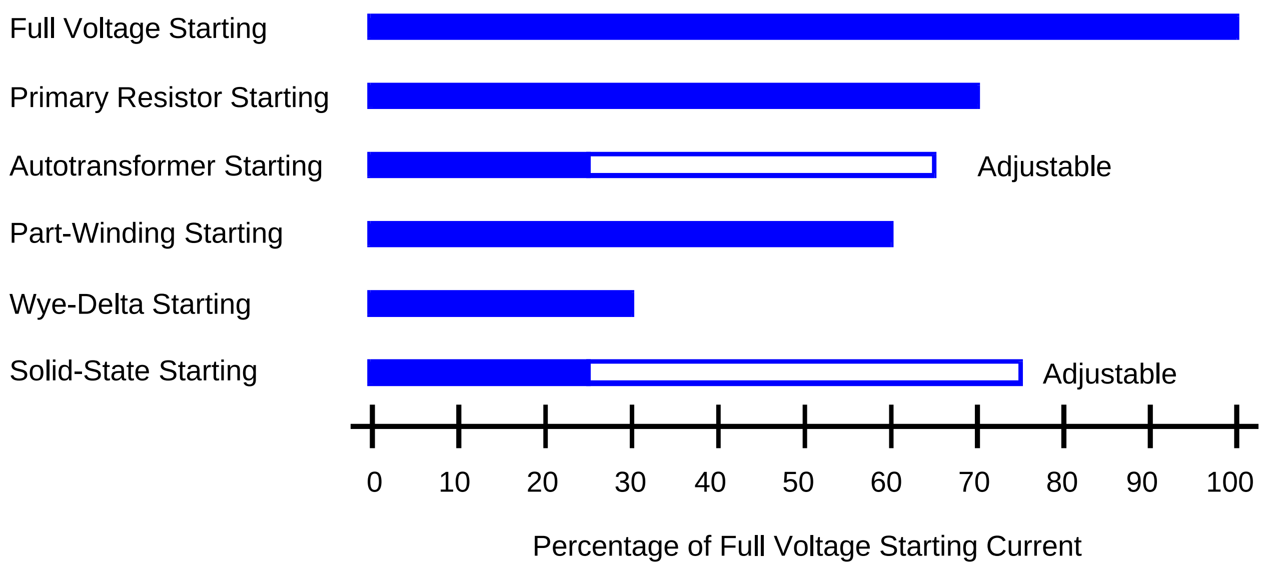
A3.5.2. SCRs are small in size, rugged, and have no contacts. The disadvantage of solid-state starting is the relatively high cost compared to other options.

A3.6. Comparison of Reduced Voltage Starting Methods:

A3.6.1. Several reduced voltage starting methods are available. However, there is not a single method that is appropriate for all applications. The amount of reduced current, the amount of reduced torque, and the cost of each method must be considered when selecting the starting method. Also, the selection cannot focus only on the method that reduces the most starting current. If the starting current is reduced too low, the motor will not start and the overloads will eventually trip.

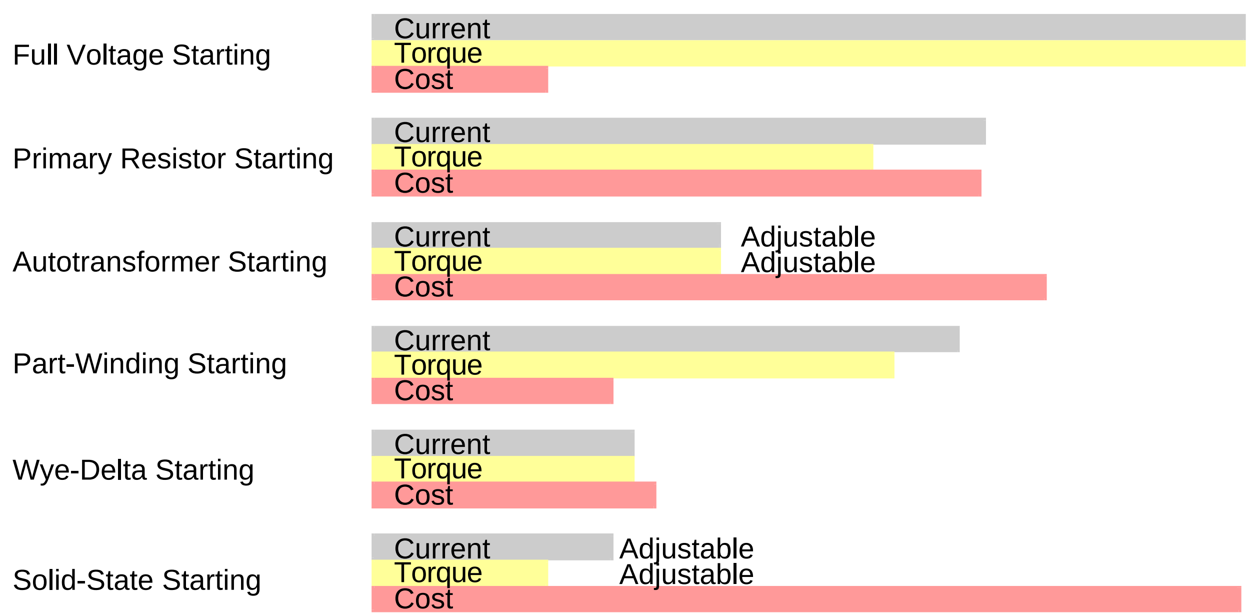
A3.6.2. The amount of starting current reduction can be compared for each reduced voltage starting method. The starting current reduction is adjustable with autotransformer or solid-state starting. Some primary resistor starting methods have some adjustment capability, while other available types have no adjustment capability. Part-winding and wye-delta methods are not adjustable. Figure A3.4 shows the starting current that can be achieved with each type.

Figure A3.4. Starting Current With Different Reduced Voltage Starting Methods.



A3.6.3. The reduction in applied torque can also be approximated for each method. As with the starting current, the torque reduction is adjustable with the autotransformer and the solid-state methods. Autotransformer starting is adjustable to the degree allowed by the transformer types and solid-state starting is adjustable throughout its range. With each method, the applied torque must be greater than the load torque or else the overloads will trip. For this reason, the torque requirements must be considered when selecting the reduced voltage starting method. Figure A3.5 provides a summary of the current, torque, and cost of each method.

Figure A3.5. Comparison of Current and Torque Reduction With Different Starting Methods.



A3.6.4. The first consideration is the reduction in starting current or starting torque compared to the load requirements when selecting a reduced voltage starting method. Second, cost should be considered, particularly because of the wide variation in cost between methods.

A3.6.5. The primary resistor starting method is used when it is necessary to restrict inrush current to a predetermined value or increments. Primary resistors can be designed for almost any current inrush limit and they provide smooth motor acceleration.

A3.6.6. The autotransformer starting method provides the highest possible starting torque per ampere of line current and is the most effective means of motor starting for applications where the inrush current must be reduced with a minimum sacrifice of starting torque. Multiple taps are provided to allow for field adjustment. Cost must be considered because this method is more expensive.

A3.6.7. Part-winding starting is simple in construction and has a low cost. It provides a simple method for starting low-torque loads. The cost is lower because no external resistors or transformers are required.

A3.6.8. Wye-delta starting is suitable for applications involving long accelerating times or frequent starts.

A3.6.9. Solid-state starting provides smooth, stepless acceleration, and it controls motor voltage, current, and torque during the acceleration. This method provides the most control over a wide range, but it is also the most expensive method.

A3.6.10. Table A3.1 summarizes the advantages and disadvantages of each reduced voltage starting method.

Table A3.1. Comparison of Reduced Voltage Starting Methods.

Starting Method	Motor Volts	Line Current	Startin g Torque	Cost	Advantages	Disadvantages	Applications
Full Voltage	100%	100%	100%	Lowest	Inexpensive and readily available; simple to maintain; maximum starting torque	High inrush current and high starting torque	Many
Primary Resistor	65%	65%	42%	High	Smooth acceleration and high power factor during start; can have multiple resistors for increments	Low torque efficiency; starting times exceeding 5 seconds require expensive resistors	Belt and gear drives, conveyors
Auto-Transformer	80% 65% 50%	64% 42% 25%	64% 42% 25%	High	Provides highest torque per ampere of line current; suitable for longer starting periods, motor current is greater than line current during starting	Most expensive option for lower horsepower ratings; low power factor; large physical size	Blowers, pumps, compressors, conveyors
Part Winding	100%	65%	48%	Low	Least expensive reduced voltage method; most dual voltage motors can be started part winding on lower voltage; small size	Not suitable for high inertia, long starting loads; requires special motor design above 230 volts; care must be taken to avoid overheating	Reciprocating compressors, pumps, blowers, fans
Wye-Delta	100%	33%	33%	Medium	Suitable for high inertia, long acceleration loads; high torque efficiency; good for low inrush requirements	Requires special motor; low starting torque; open transition design can cause intermediate inrushes	Centrifugal compressors
Solid-State	Adj.	Adj.	Adj.	Highest	Best soft start capability with extensive adjustment capability	High cost, requires specialized maintenance and installation; transients can damage unit; requires ventilation	Machine tools, hoists, conveyors

Attachment 4

ASD EQUIPMENT SPECIFICATIONS

A4.1. The following is a sample specification for an ASD. The specifications provided below are a sample only and will not be appropriate for all applications; each application requires tailored specifications. ASDMaster® can also be used to generate the equipment specifications.

Table A4.1. Example ASD Specification.

Specification Number	Description
1	APPLICATION
1.1	The ASD shall control the variable torque centrifugal fan over a speed range from 800 to 1750 rpm with a tolerance of 5 percent. The ASD shall sustain an overload of 150 percent for one minute. The ASD shall provide a starting torque of 30 percent of full load torque.
2	MOTOR INFORMATION
2.1	The ASD shall be used to control a new motor. The motor has the following characteristics: Enclosure: TEFC Rated power: 90 hp Rated current: 115 amps Rated speed: 1775 rpm Rated frequency: 60 hz Rated voltage: 460 volts Rated efficiency: 95 percent Maximum allowable speed: 2130 rpm NEMA type: B Insulation class: F Service Factor: 1.15 Bearings: Antifriction
3	MOTOR INTERFACE
3.1	The ASD shall properly interface with the motor, and shall not affect the motor's rigid coupling.
3.2	The driven motor will be a premium-efficiency machine.
3.3	The motor possesses imbedded thermal protection.
3.4	The nominal cable length between ASD and motor is to be 30 feet.
4	TORSIONAL ANALYSIS
	No torsional analysis is required.
5	POWER SUPPLY
5.1	The ASD shall operate from an electrical supply with the following specifications: Phase Configuration: Three phase Voltage: 480 volts Voltage Tolerance: plus 10 percent Voltage Tolerance: minus 10 percent for 0.5 seconds

Specification Number	Description
	Frequency: 60 hz plus or minus 2 hz Available short-circuit MVA at the point of common coupling: 150 MVA Transient Voltage: 86 percent of peak supply voltage for a duration of 1.5 milliseconds.
5.2	The ASD shall operate at a displacement power factor of 0.95 or better under all speed and load conditions. The ASD shall not generate notches or transient voltage disturbances at the electric supply.
5.3	The ASD shall incorporate input transient suppression components as determined by NEMA standards. The ASD shall incorporate a dc bus reactor and/or ac line reactors to limit harmonic current injection. IEEE 519-1992 shall be used to determine the necessity for harmonic current filters.
6	ENCLOSURE TYPE
6.1	The enclosure will be mounted indoors and shall be of type NEMA 4 suitable for a 104 °F (40 °C) maximum and a 23 °F (-5 °C) minimum ambient temperature.
6.2	Enclosure dimensions shall be adequate to allow a heat rejection of 10 kW.
6.3	The enclosure shall be painted ANSI 61 with wet type paint. For interior surfaces ANSI 61 paint shall be used.
7	ENCLOSURE OPTIONS
7.1	These instruments shall be mounted on the front of the enclosure: voltmeter, ammeter, frequency.
7.2	These control components shall be mounted on the front of the enclosure: start pushbutton, stop pushbutton, reset pushbutton, bypass switch.
8	ASD SYSTEM ENVIRONMENT
8.1	The ASD shall be contained within a suitable enclosure.
8.2	The ASD shall provide rated output in an ambient temperature ranging from 23 °F (-5 °C) to 104 °F (40 °C).
8.3	The ASD shall be fully operational with a humidity level of 95 percent, non-condensing.
8.4	The ASD shall be operated at an altitude of 3,000 feet (914 meters) above sea level.
8.5	The acoustic noise generated by the equipment, measured 3 feet from the enclosure, shall not exceed 65 dBA above ambient at any operating speed.
8.6	The ASD shall be fan-induced flow cooled. The required path of air across the equipment shall be clearly documented together with the quantity of air required to provide full output rating.
9	REQUIRED EFFICIENCY
9.1	The efficiency of the ASD shall be greater than 95 percent at rated output.
9.2	The highest combined efficiency of both ASD and motor shall be achieved at 75 percent of motor rated speed.
10	RELIABILITY
10.1	The ASD shall have a proven reliability of 50,000 hours Mean Time Between Failures (MTBF) demonstrated through field installations in applications similar to the one covered in this specification.
10.2	The Mean Time To Repair (MTTR) shall be 1.5 hours and shall be achieved by replacement of an ASD component.
10.3	The equipment shall be designed for a 15 year life.

Specification Number	Description
11	SYSTEM PROTECTION
11.1	Protection shall be provided for the following electric power supply side conditions: overvoltage, undervoltage.
11.2	Protection shall be provided for the following load motor side conditions: line to line short, line to ground short, timed overcurrent.
12	INPUT SIGNALS
12.1	Remote speed control shall be achieved using an isolated 4-20 mA analog signal.
12.2	Hardwired control signals shall be included in the ASD. Each circuit shall be isolated in a 2 wire format designed to transmit a 5V dc signal. A separate circuit shall be provided for the following: start/stop.
13	OUTPUT SIGNALS
13.1	Isolated analog output signals at a level of 4-20 mA shall be provided for the following ASD parameters: output power, current, voltage, speed, frequency.
13.2	Isolated hardwired circuits having a two-wire format designed to operate at 5V dc shall transmit the following states: tripped, stopped, bypass.
14	CONTROL ADJUSTMENTS
	The ASD control shall permit the following adjustments:
14.1	Current limit adjustable from 50 to 150 percent of rated output current. At this level the ASD shall trip after 1 minutes.
14.2	Voltage boost adjustable from 5 to 100 at motor full load slip frequency.
14.3	Voltage-to-frequency ratio adjustable from 5 to 10 volts/hz.
14.4	Overspeed trip adjustable from 90 to 150 percent of rated motor speed.
14.5	The ASD shall incorporate an energy-saving mode of operation.
15	SYSTEM ADJUSTMENTS
15.1	The ASD modulation frequency shall be 1200 hz to ensure optimum motor performance can be obtained.
15.2	The ASD shall provide adjustable slip compensation and shall achieve 1 percent speed regulation at rated load.
15.3	Up to one skip frequency or frequency-avoidance band shall be selectable.
16	SPEED ADJUSTMENTS
	The ASD control shall permit the following adjustments:
16.1	Minimum speed adjustable from 0 percent to 70 percent of rated motor speed.
16.2	Maximum speed adjustable from 30 to 120 percent of rated motor speed.
16.3	Acceleration time adjustable from 5 to 60 seconds.
16.4	Deceleration time adjustable from 5 to 60 seconds.
17	FAULTS AND ALARMS
17.1	Provision shall be made for the generation of a unique alarm signal for each of the following conditions: logic power failure, speed error, communications failure.
17.2	Provision shall be made for the generation of a unique trip state for each of the following conditions: logic power failure.
17.3	The ASD shall progressively slow the speed of the load machine as a mechanical overload is applied. The ASD shall return to the selected speed after the overload has been removed.
17.4	The ASD shall be capable of 3 automatic restarts.

Specification Number	Description
17.5	The ASD shall be capable of catching a spinning motor and driving the speed to the set point.
18	DIAGNOSTICS
18.1	The ASD shall include an operators liquid crystal display (LCD) that will automatically display an ASD fault and identify the replaceable module required.
18.2	Fault information shall be transmitted on the serial communications connection specified in the section entitled OUTPUT SIGNALS.
18.3	Alarm and trip signals shall be connected to hardwired outputs as specified in the section entitled OUTPUT SIGNALS.
19	REACTORS AND TRANSFORMERS
19.1	The ASD shall be provided with ac input line reactors of 3 percent impedance. Reactors shall be specifically designed for inverter duty application.
20	BYPASS CIRCUIT
20.1	The ASD shall be provided with a manual padlockable 60 hz bypass.
20.2	The bypass circuit shall have the following features: thermal protection of motor, mechanical interlock, isolate ASD (yet permit testing).